EFFECT OF ROLL OF SHIP ON FALL OF SHOT WHEN USING DIRECTOR FIRE

WILLIAM P. O. CLARKE
ALBERT NOBLE

[illegible]
U. S. Naval Postgraduate School
Monterey, California

Mont 108
8854

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By

William P.O.Clarke, Lt.USN

and

Albert Noble, Lt.USN

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Professor A. L. Merrill, Sec.,
Massachusetts Institute of Technology,
Cambridge, Mass.

Dear Sir:

In accordance with the requirements for the degree of Master of Science in Mechanical Engineering, we submit herewith thesis entitled, "Effect of Roll of Ship on Fall of Shot When Using Director Fire."

Respectfully submitted,

TABLE OF CONTENTS

Page

CONCLUSIONS 1

SECTION I - Introduction 3

SECTION II - Errors due to Motion of Director Relative to Fixed Plane of Ship 4-24

Computation of U.S.S.Florida 6

Computation of U.S.S.North Dakota 16

SECTION III - Errors Caused by Motion of Gun during Firing Interval. 25-33

SECTION IV - Error due to Velocities Imparted to Projectile by motion of ship 34-43

(a) Center line guns 38

(b) Guns not on Center Line. 41

SECTION V - Charts II and III. Method of Construction and Instructions for their Use. 44-46

SECTION VI - Description of Test on Mast on U.S.S. North Dakota, and Analysis of Results Obtained Therefrom. 47-55

SECTION VII- Curves, charts and Diagrams 56-59

Load-Deflection Curves, U.S.S. North Dakota 56-62

Curvature of Mast 63-65

Error Correction Charts 66-68

CONCLUSIONS

I. That the cage masts as installed on the U.S.S. North Dakota do not cause any appreciable error in range in the fall of shot when using the Directorscopes installed in their tops.

II. That the motion of the gun, due to the angular velocity of rolling of the ship does cause an error in range in the fall of shot. That the amount of this error depends on the angle of train, and the angular velocity of the rolling of the ship.

III. That the velocities imparted to the shell in the direction at right angles to the tangent to the trajectory, at the muzzle of the gun do cause an error in range in the fall of shot.

IV. That the velocities in other directions cause very small errors in range in the fall of shot, which may be neglected.

V. That the major calibre guns should always be fired when the ship is rolling in the same direction.

VI. In firing guns that cannot wait for the roll, these errors in range in the fall of shot referred to in II and III should be kept in mind by the control officer.

VII. By the use of easily constructed charts, the errors referred to in II and III may be quickly calculated, with the instruments now at hand.

SECTION I

The purpose of this thesis is the Investigation of range error introduced in the fall of shot by the rolling of the ship, when using Director Fire and the method of correcting for these errors for the initial shot. The conditions to be investigated which cause this error in the fall of shot are:-

(1) Motion of the Sighting instrument relative to a fixed plane on the ship.

(2) Motion of the gun during the firing interval, and

(3) Motion of the ship imparting velocities to the projectile which tend to move it out of its calculated path.

SECTION II

Error Due to Motion of Director Relative to a Fixed Plane on the Ship.

The error due to the motion of the Sighting instrument relative to a fixed plane on the ship, is caused by movement of the supporting structure for this instrument, relative to a fixed plane on the ship. These Sighting Instruments, or Directorscopes, are mounted in various positions on the ship, and with the exception of those in the fore and main tops, no error is considered to be introduced by the motion of the ship when rolling.

It is desired, however, to find what error, if any, is introduced by the ship's motion when using the fore or main top directors.

These instruments are mounted in the top of a cage mast with approximately 90 feet of unsupported length, When the ship rolls, these masts are subjected to a transverse loading due to gravity, which is a static force, and also due to an accelerating force, which is a dynamic force. The forces acting on the mast will cause it to deflect in one of three manners:-

(1) As a cantilever beam, with both a change in slope, and a deflection.

(2) As a pantagraph, with a deflection, but no change in slope, or,

(3) A combination of (1) and (2).

If the mast deflects as a beam, the change in slope will introduce an error in the directorscope, except when the ship is in the upright position.

If the mast deflects as a pantagraph, no angular error is introduced.

If the mast deflects as a combination of a beam, and a pantagraph, an angular error will be introduced, which may be proportional to the loading on the mast, or may not, depending upon the qualities of the mast itself.

In order to investigate this subject, the change of slope and the deflection for the Foremast of the U.S.S. Florida that should be expected for a 10° roll, is computed, assuming the Mast to act like a beam, supported at one end.

Formulae used:

FLORIDA

$$I = A\left[2r_1^2 + 4\overline{r_1 \sin 75^\circ}^{\,2} + 4\overline{r_1 \sin 60^\circ}^{\,2} - - - 4\overline{r_1 \sin 15^\circ}^{\,2}\right]$$

where,

I = Transverse moment of Inertia of Mast.

N = Number of elements

A = Area of one element

r = Radius of mast

$$i_1 = \frac{F\,l^2}{2\,EI}\;; \qquad i_2 = \frac{M\,l_1}{2\,EI}\;; \qquad i_3 = \frac{F\,a^2}{2\,EI}$$

F = Shear on the mast at any section.

l = length of section of mast under consideration

E = Modulus of Elasticity in pounds per square inch

M = Bending Moment at point, 1, distant from fixed point.

a = distance of single concentrated load not at free end, from the end considered as fixed.

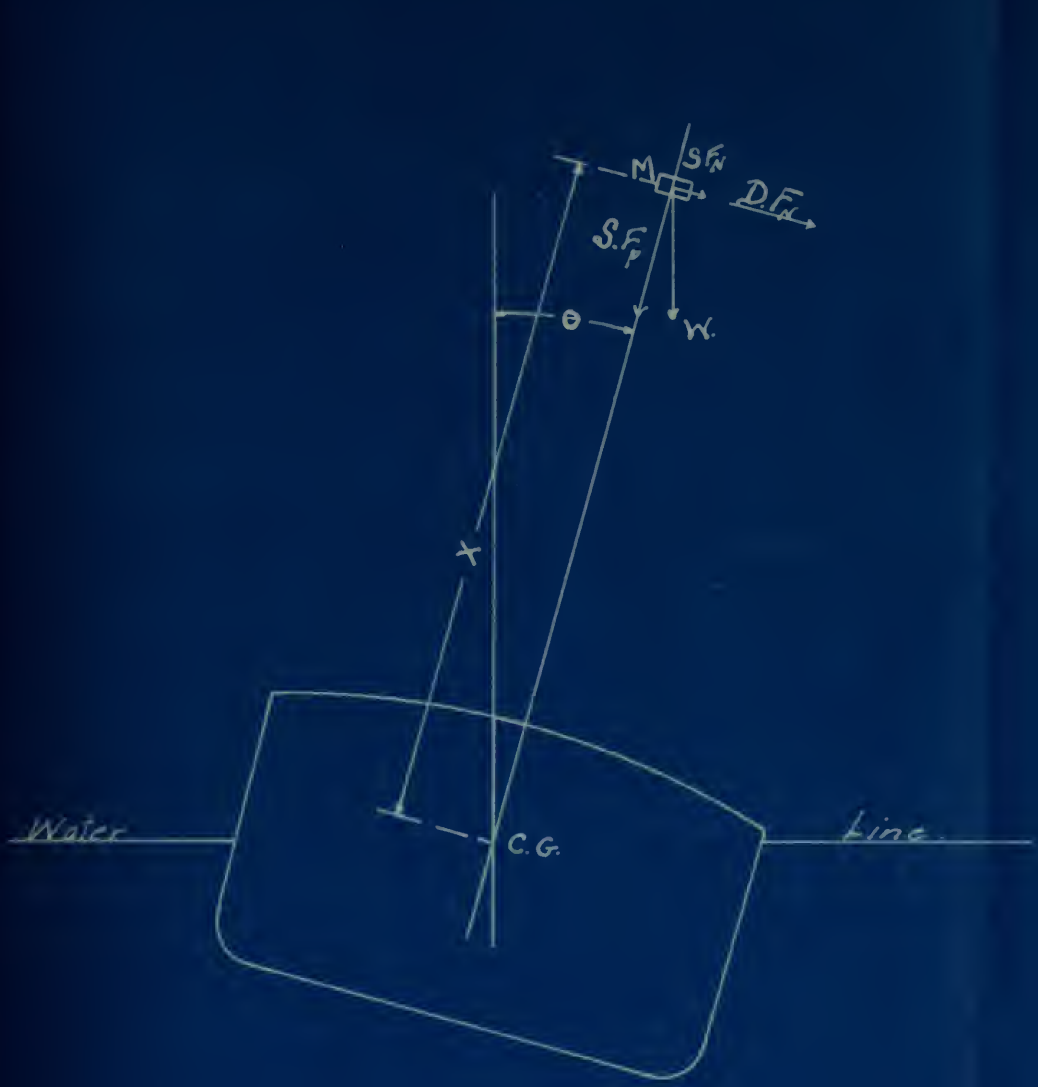
i = slope of mast in radians at free end

α = angular acceleration in radians

$$= \frac{\pi^3}{180} \times \frac{\theta}{(T)^2}$$

θ = angle of roll, in degrees

T = half period of ship in seconds.



C.G is the Centre of Gravity of Ship.

θ is the angular displacement at any instant from the vertical position.

M is a particle whose Mass is M.

$S.F_n$. is the Static force due to gravity of the Mass M. Normal to the axis of the Mast.

$S.F_p$. is the Static force due to gravity of the Mass M parallel to the axis of the Mast.

$D.F_n$. is the Dynamic force of Mass M due to acceleration

X is the distance of the Mass M from the C.G.

A particle, whose weight is W, at x feet above the center of rotation, which in this case is the c.g. of the ship, will exert the following forces normal to the vertical axis of the mast:-

$$\text{Static Force} = W \quad \sin\theta$$

$$\text{Dynamic Force} = \frac{W}{g} \times \alpha$$

This loading is that of a cantilever beam under transverse loads.

Section I. Base of mast to height of 19.468 ft. above base.
Length = 19.468 ft.

Bottom radius = 110.6 inches

Top radius = 86.0 inches

$$\text{Area cross section one element} = \frac{\pi(\overline{26.26}^2 - \overline{2.375}^2}{4}$$

$$= .98172 \text{ sq.in.}$$

$$I_{\text{Bottom}} = .98172 \quad 2 \times \overline{110.6}^2 + 4(\overline{110.6 \sin 75}^2 + \overline{110.6 \sin 60}^2$$

$$- \overline{110.6 \sin 15}^2 = 292{,}025 \ \overline{\text{in.}}^4$$

$$I_{\text{Top}} = 292025 \times \frac{\overline{86.0}^2}{110.6} = 177{,}500 \text{ In.}^4$$

Section II. 19.468 ft. to 38.72 ft. above base
Length = 19.28 ft.

Bottom radius = 86"

Top radius = 65.6"

Area = $II_4(\overline{2.125}^2 - \overline{1.875}^2) = .7854$ Sq.In.

$I_{top} = 81,130$

$I_{bottom} = 139,429$

Section III. 38.728 ft. to 56.418 ft. above base
Length = 17.69 ft.

Bottom radius = 65.6"

Top radius = 53.5"

$$\text{Area} \quad \frac{\pi(\overline{1.75}^2 - \overline{1.5}^2}{4} = .6734$$

$I_{bottom} = 65,800$

$I_{top} = 43,766$

Section IV. 56.418 ft. to 81.376 ft. above base
Length = 24.958 ft.

Bottom radius = 53.5 in.

Top radius = 56.0 in.

Area = .6734 sq.in.

$I_{bottom} = 21,883$ In.^{4}

$I_{top} = 22,911$ In.^{4}

BRASS TUBING

Section I

2 5/8   1/8" Thick   Wt/foot = 5.06 #

Section II

2 3/8   1/8" Thick   Wt/foot = 3.07 #

STEEL TUBING

Sections III & IV

1 3/4   1/8" Thick   Wt/foot = 2.17 #

Wt. per Height of Mast per element.

$$\frac{5.06}{\cos 15^\circ} = \frac{5.06}{.96593} = 5.25 \text{ lbs.}$$

$$\frac{3.07}{\cos 15^\circ} = \frac{3.07}{.96593} = 3.18 \text{ lbs.}$$

$$\frac{2.17}{\cos 15^\circ} = \frac{2.17}{.96593} = 2.25 \text{ lbs.}$$

Section (1) 48 x 5.25 = 252 lbs.

Section (2) 48 x 3.18 = 152.5 lbs.

Section (3) 48 x 2.25 = 108.0 lbs.

Section (4) 24 x 2.25 = 54.0 lbs.

When ship is inclined 10° -

Static Force acting at Right angle to C.L. of Mast =

Section (1) 252 sin 10° = 252 x .17365 = 43.8 lbs.

Section (2) 152.5 sin 10°=152.5 x .17365=26.5 lbs.

Section (3) 108.0 sin 10°=108.0 x .17365=18.75 lbs.

Section (4) 54.0 sin 10°= 54 x .17365 = 9.375 lbs.

Increasing these weights by 25% for fittings, rings, etc. the weights for these sections become:-

Section (1)	54.8 lbs.
Section (2)	33.1 lbs.
Section (3)	23.4 lbs.
Section (4)	11.7 lbs.

Assuming a roll of 10° for the solution of this problem and assuming a period of 12 seconds for a complete roll:-

$$\alpha = \frac{\pi^3}{180} x \frac{10}{(6)^2} = .0478 \text{ radians/sec.}$$

Dynamic force acting is directed away from center position and perpendicular to C.L. of mast and

$= F = \frac{W\alpha}{g} x.$

$\frac{-}{g} = \frac{.0478}{32.17} = .00149$

At base of mast R = 32.615 $x \frac{\alpha}{g} = .0486$

Top of Section I, R = 52.084 $x \frac{\alpha}{g} = .0775$

Top of Section II, r = 71,323 $x \frac{\alpha}{g} = .1062$

Top of Section III, r = 89,013 $x \frac{\alpha}{g} = .1325$

Top of Section IV, r =114,071 $x \frac{\alpha}{g} = .1698$

At searchlight platform r = 78 $r \frac{\alpha}{g} \overset{\alpha}{=} .1162$

		Average
.0486 x 252 =	12.25	
.0775 x 252 =	19.5	W_1 = 15.9 lbs./ft.
.0775 x 152.5=	11.8	
.1062 x 152.5=	16.2	W_2 = 14.0 lbs./ft.
.1062 x 108 =	11.5	
.1325 x 108 =	14.3	W_3 = 13.9 lbs./ft.
.1325 x 54 =	7.15	
.1698 x 54 =	9.17	W_4 = 8.16 lbs./ft.

LOADING

Platform	9750		
Men	600		
Instrument	1500		
Pipe	165		
Topmast	1270	Static	Dynamic
	13285	2310	.1698 = 2260

78.' Search light Platform Loading:

Platform	6000	Static	Dynamic
Search lights	7000		
	13000	x.17365=2259	x .1162= 1510

Concentrated Loads:

	78'	114'
Static	2259	2310
Dynamic	1510	2260
	3769 lbs	4570 lbs

Assumption for approximate Solution.

Uniform Loading = Dynamic + Static Forces

Section I = 15.9 + 54.8 = 70.7 lbs.
Section II = 14.0 + 33.1 = 47.1
Section III = 13.9 + 23.4 = 37.3
Section IV = 8.2 + 11.7 = 19.9

That the average I are taken as:-

Section I = 240,000 in.^{4}
Section II = 110,000 in.^{4}
Section III = 54,000 in.^{4}
Section IV = 22,000 in.^{4}

Modulus of Elasticity:

Section I	16,000,000	lbs/sq.in.	
Section II	16,000,000	"	"
Section III	29,000,000	"	"
Section IV	29,000,000	"	"

Concentrated Loading:

Section III 3769 # at 45' 6"
Section IV 4570 # at 81' 4"

Section IV

$$i_1 = \frac{4570 \quad \overline{24.958}^2 \times 144}{2 \times 22,000 \times 29,000,000} = .0003218 \text{ radians}$$

$$i_2 = \frac{19.9 \times 24.958 \times \overline{24.958}^2 \times 144}{6 \times 22,000 \times 29,000,000} = .00001168 \text{ radians}$$

Section III

$$i_1 = \frac{4570 \times 24.98 + \frac{19.9 \times \overline{24.958}^{2}}{2} \qquad 12 \times 17.69 \times 12}{54{,}000 \qquad \times 29{,}000{,}000}$$

$$= .0001954 \text{ radians.}$$

$$i_2 = \frac{37.3 \times 17.69 \times \overline{17.69}^{2} \times 144}{6 \times 54000 \times 29{,}000{,}000} = .000003162 \text{ radians}$$

$$i_3 = \frac{3769 \times \overline{6.748}^{2} \times 144}{2 \times 54000 \times 29{,}000{,}000} = .00000796 \text{ radians}$$

$$i_4 = \frac{(4570 + 3769 + 19.9 \times 24.958)\ \overline{17.69}^{2} \times 144}{29{,}000{,}000 \times 54000} = .0002545 \text{ radians}$$

Section II

$$i_1 = \frac{\left(4570 \times 42.648 + 19.9 \times 24.958 \times 30.169 + 37.3 \times \frac{\overline{17.69}^{2}}{2}\right) 12}{16{,}000{,}000 \times 110{,}000}$$

$$\frac{\times 19.28 \times 12}{16{,}000{,}000 \times 110{,}000} = .000339 \text{ radians}$$

$$i_2 = \frac{(4570 + 3769 + 19.9 \times 24.958 + 37.3 \times \overline{17.69}^{2})\ \overline{19.28}^{2} \times 144}{16{,}000{,}000 \times 110{,}000}$$

$$= .0002893 \text{ radians.}$$

$$i_3 = \frac{47.10 \times 19.28 \times \overline{19.28}^{2} \times 144}{6 \times 16{,}000{,}000 \times 110{,}000} = .0000460 \text{ radians}$$

Section I

$$i_1 = \frac{(4570 \times 61.928 + 19.9 \times 49.449 \times 24.958 + 37.3 \times 28.125 \times 17.69)}{16{,}000{,}000 \times 240{,}000}$$

$$\frac{19.468 \times 12 \times 12}{16{,}000{,}000 \times 240{,}000} = .000165 \text{ radians.}$$

$$i_2 = \frac{(4570 + 19.9 \times 24.958 + 37.3 \times 17.69 + 47.1 \times 19.28)\overline{19.468}^2 \times 144}{16{,}000{,}000 \times 240{,}000}$$

$$= .0001477 \text{ radians.}$$

$$i_3 = \frac{70.7 \times 19.468 \times \overline{19.468}^2 \times 144}{6 \times 240{,}000 \times 16{,}000{,}000} = .00000326 \text{ radians}$$

$$i_{total} = \sum\left[i_1 + i_2 + i_3 + i_4 \; - - - \; i_{12}\right] =$$

$$.0017848 \times 57.3 \times 60 = 6'.13$$

CALCULATIONS

ON

NORTH DAKOTA

A change in slope of 6'20" is not excessive for an angle of roll of 10°, and shows that, should this be corroborated by experimental data, the cage mast is a suitable platform for all practical purposes, for a director station.

With the purpose of investigating the nature and magnitude of the slope when under a system of loading, an actual test was made on the U.S.S.North Dakota.

The description of this experiment is as follows:-

A steel wire cable was run between the fore and main masts, and made fast to the rings supporting the tops, and into which the mast elements are made fast. Load was applied by means of a turnbuckle, and was measured by a steelyard and 500 lb. spring balance. Deflection of the mainmast was measured at 3 places, using a surveyors transit, and scales fastened to the mast. On the Foremast, only the deflection at the top could be measured, as the bridge and search light platform screens obstructed the line of sight.

Gunners quadrants were used in each top to measure the change in slope.

A steel tape was run between the two masts, and the distance between two fixed points measured for each load. This served as a check on the transits.

For the data obtained from this test see pages

The problem now is to apply the data obtained from the experiment, to the actual conditions which exist when the ship is at sea.

$$\text{Area 2'' 1/2 tubes} = \pi\left(\frac{\overline{2.5}^{2} - \overline{2.25}^{2}}{4}\right) = .934 \text{ sq.in.}$$

$$\text{Area 1'' 3/4 tubes} = \pi\left(\frac{\overline{1.75}^{2} - \overline{1.5}^{2}}{4}\right) = .637 \text{ sq.in.}$$

r = 122.37 in.
0 ft.

$$I_1 = \frac{48}{2} \times \overline{122.37}^{3} \times .934 = 412{,}000.\ \text{IN}^4$$

r = 101.5 in.
h = 14.75 ft.

$$I_2 = \frac{48}{2} \times .934 \times \overline{101.5}^{3} = 234{,}800.\ \text{IN.}^4$$

r = 101.5 in.
h = 14.75 ft.

$$I_3 = \frac{48}{2} \times .637 \times \overline{101.5}^{3} = 160{,}000.\ \text{in}^4$$

r = 81.875 in.
h = 29.78 ft.

$$I_4 = \frac{48}{2} \times .637 \times \overline{81.875}^{3} = 83700.\ \text{IN}^4$$

r = 56.3
h = 56.70

$$I_4 = \frac{48}{2} \times .637 \times \overline{56.3}^{3} = 27{,}300.\ \text{IN}^4$$

$r = 56.3$ in.
$h = 56.70$ ft.

$$I_5 = \frac{24}{2} \times .637 \times \overline{56.3}^{\,3} = 13{,}650. \ \mathrm{IN}^4$$

$r = 53.$ in.
$h = 70.$ ft.

$$I_6 = \frac{24}{2} \times .637 \times \overline{53}^{\,3} = 11{,}370. \ \mathrm{IN}^4$$

$r = 57.$ in.
$h = 81.4$ ft.

$$I_7 = \frac{24}{2} \times .637 \times \overline{57}^{\,3} = 14{,}150 \ \mathrm{IN}^4$$

Section I

$E = 16{,}000{,}000$ #/sq.in.

$I = 280{,}000$ In.^{4}

$l = 14{,}75$ ft.

Cross sectional area 1 element = .934 sq.in.

Section II

$E = 16{,}000{,}000$ lbs./sq.in.

$I = 120{,}000$ in.^{4}

$l = 15.0$ ft.

Cross sectional area 1 element = .637 sq.in.

Section III

$E = 29{,}000{,}000$ lbs./sq.in.

$I = 50{,}000$ in.^{4}

$l = 26.9$ ft.

Cross sectional area 1 element = .637 sq.in.

Section IV

$E = 29{,}000{,}000$ lbs./sq.in.

$I = 14{,}000$ in.^{4}

$l = 24.7$ ft.

Cross sectional area 1 element = .637 sq.in.

Data for these computations taken from page 59
Run #2, Readings (2) and (6)
Δ Load = 2800, $\Delta i = 2' 50''$, $\Delta y = \frac{14}{32}''$

COMPUTATIONS

$$i_4 = \frac{2800}{2} \times \frac{\overline{24.7}^2 \times 144}{29{,}000{,}000 \times 14000} = .000330 \text{ radians}$$

$$M = 2800 \times 24.8 \times 12$$

$$l_3 = \frac{2800 \times 24.7 \times 12 \times 26.9 \times 12}{29{,}000{,}000 \times 50{,}000} + \frac{2800}{2} \times \frac{\overline{26.9}^2 \times 144}{29{,}000{,}000 \times 50{,}000}$$

$$= .0002852 \text{ radians.}$$

$$l_2 = \frac{2800 \times 12 \times 51.6 \times 15.0 \times 12}{16{,}000{,}000 \times 120{,}000} + \frac{2800}{2} \times \frac{\overline{15.0}^2 \times 144}{16{,}000{,}000 \times 120{,}000}$$

$$= .0001841 \text{ radians.}$$

$$l_1 = \frac{2800 \times 66.6 \times 14.75 \times 144}{280{,}000 \times 16{,}000{,}000} + \frac{2800}{2} \times \frac{\overline{14.75}^2 \times 144}{280{,}000 \times 16{,}000{,}000}$$

$$= .0001864 \text{ radians}$$

$$i = i_1 + i_2 + i_3 + i_4 = .0009587 \text{ radians.}$$

$$= 3'.3$$

$$= 3' \, 18''$$

But the actual change in slope was 2' 50" or 2'.83".

Substituting this value for i in the formula,

$$i = \frac{F\,l^2}{2\,EI},$$

a value for EI may be found.

$$EI = \frac{\overline{81.4}^{\,2} \times 144 \times 2800}{.000823 \times 2}$$

Substituting this value for EI in,

$$V = \frac{Fl^3}{3\,EI} = \frac{2800 \times \overline{81.4 \times 12}^{\,3}}{3\,EI} = ''.483 = \frac{15.45''}{32}$$

$$V = \frac{15.45''}{32}$$

But the measured deflection was $\frac{14}{32}$, which is less than the computed value.

From the above data, the conclusion is reached that the various bridge structures act as partial supports, and in doing so decrease the effective length of the mast as a beam.

$$\text{Since } i = \frac{Fl^2}{2\,EI},$$

$$\text{and } V = \frac{Fl^3}{2\,EI},$$

it is readily seen that with a reduction in l, the length of the beam, affects V to a greater extent than it affects i.

Since, however, the slope varies directly with the Force applied, we may compute the actual change in

slope for a given load, by using the data found from the experiment.

This slope found will be correct, provided the load is applied at the same point.

When considering the load due to the weight of the elements, and the concentrated load at the search light platform, it is recognized that an error will be introduced by keeping the length of the beam constant at 81.4 ft., instead of allowing for a reduction in length, due to the partial supporting forces of the various bridge structures. But since the total change in slope caused by this loading is small, no material error will be introduced by this assumption.

Change in slope due to concentrated load in the Top.

$$F = W \sin\theta + \frac{W}{g} r\alpha$$

$$\alpha = \frac{\pi^3}{180} \times \frac{\theta^\circ}{(t)^2}$$

$$F = W \left[\sin\theta + \frac{r}{g} \frac{\pi^3}{180} \frac{\theta}{t^2} \right]$$

For angles under consideration 0° to 10° assumption that Sin $\theta = \theta$ may be used without material error. Then,

$$F = W \left[\theta^{r.} + \frac{r}{g} \frac{\pi^3}{180} \times \frac{\theta^0}{t^2} \right] = W\theta \left[1 + \frac{r}{g} \frac{\pi^2}{t^2} \right]$$

F = Force Normal to axis of Mast.

where W = Weight in lbs. at top

θ = Amplitude of roll in radi~~us~~ans

r = Distance from C.G. of Weight, W.

q = 32.17 ft./sec.^{2}

t = Time of half period in seconds.

$$\text{Equivalent EI} = \frac{\overline{81.4}^2 \times 144 \times 2800}{.000823 \times 2}$$

$$F = W\theta \left[1 + \frac{115}{32.17} \times \frac{\pi^2}{49} \right]$$

$$= W\theta \left[1 + .729 \right]$$

$$F = 1.729\ W\theta$$

$$i = \frac{Fl^2}{2\ EI} = \frac{1.729\ W\theta l^2}{2\ EI} \text{ radians}$$

$$i = \frac{1.729\ W\theta \times .000823 \times 2 \times \overline{81.4}^2 \times 144}{2 \times \overline{81.4}^2 \times 144 \times 2800} \text{ \sout{minutes}}$$

W = Weight in top, assumed to be 10,000 lbs.

$$i = \frac{1.729\ W \times \theta \times .000823}{2800} = K\ W\theta^\circ$$

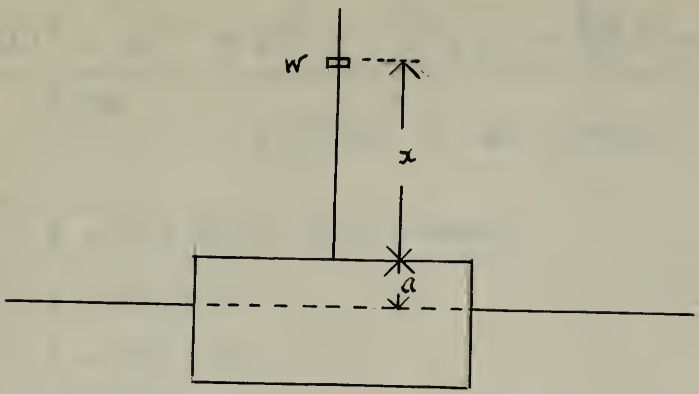
$$i = \frac{1.729\ W\theta^\circ \times .000823}{2800}$$

$$i = W\theta^\circ\ .0000005075$$

$i = .005075\ \theta^\circ$ = slope in degrees

$i = .3045\ \theta^\circ$ = slope in minutes.

Considering next the uniform load on the mast due to the weight of the elements. ~~Ref. page~~



$$F_D = \int_0^l \frac{w\,dx}{g}(a + x)\alpha = \frac{W\alpha}{g}\left[al + \frac{l^2}{2}\right]$$

l' = height at which F_1 may be considered to be concentrated

$$l' = \frac{\int dF_1 (a+x)}{\int F} = \int_0^l \frac{\frac{W\,dx}{g}(a + x)^2\alpha}{F}$$

$$= \frac{\frac{W\alpha}{g}\left[a^2x + ax^2 + \frac{x^3}{3}\right]_0^l}{F} = \frac{\frac{W\alpha}{g}\left[a^2l + al^2 + \frac{l^3}{3}\right]}{\frac{W\alpha}{g}\left[al + \frac{l^2}{2}\right]} =$$

$$l' = \frac{a^2 + al \times \frac{l^2}{2}}{a \times \frac{l}{2}}$$

$$F = Wl\left[\sin\theta + \frac{\alpha}{g}\left(a + \frac{l}{2}\right)\right]$$

$$\alpha = \frac{\pi^2}{T^2}\theta$$

$$F = W\ l\theta \left[1 + \frac{\pi^2}{t^2 g} \left(a + \frac{l}{2} \right) \right]$$

where θ is in radians.

$$i = \frac{F(l^1 - a)^2}{2\ EI} = \frac{w\ l\theta \left[1 + \frac{\pi^2}{t^2 g} \left(a + \frac{l}{2} \right) \right] (l^1 - a)^2\ 144\ x 2 x .000823}{2 \left[\overline{81.4}^2\ x\ 144\ x\ 2800 \right]}$$

where,

W = 2.2 #/ft. per element

l = 81.4 ft.

a = 33.9 ft.

t = 7 sec.

l^1 = 96.7 ft. above c.g.

= 62.8 ft. above base of mast.

$$i = \frac{2.2\ x\ 81.4\ x\ 48\ \theta \left[1 + \frac{\pi^2}{(7)^2\ \overline{32.17}} (33.9 + 40.7) \right] (62.8)^2 144}{2\ x\ \overline{81.4}^2\ x\ 144\ x\ 2800}$$

$$\frac{x\ 2\ x\ .000823}{2\ x\ \overline{81.4}^2\ x\ 144\ x\ 2800}$$

$$i = \frac{8590\ \theta \left[1.471 \right] \times \overline{6.28}^2\ x\ 144\ x\ 2\ x\ .000823}{2\ x\ \overline{81.4}^2\ x\ 144\ x\ 2800}$$

$i = .002212\ \theta^\circ$ IN Degrees.

$i = .1327\ \theta^\circ$ in minutes

Taking the searchlight platform to be 70 ft. above c.g. and weighs 6000 lbs. including search lights and platform:

$$F = 6000 \left[\sin\theta + \frac{\alpha}{g} \, 70 \right]$$

$$= 6000\,\theta \left[1 + \frac{\pi^2}{(7)^2} \, \frac{1}{32.17} \times 70 \right]$$

$$= 6000 \left[1 + .438 \right] \theta$$

$$= 8628\,\theta$$

$$i = \frac{8628\theta \times 36.1 \times 36.1 \times 144 \times .000823}{(81.4)^2 \times 144 \times 2800} = .0005050\,\theta$$

$$= .000505\,\theta^\circ \text{ in degrees}$$

$$= .0303\,\theta^\circ \text{ in minutes.}$$

Combining these changes in slope,

$$i = i_1 + i_2 + i_3$$

$$i = .3045\,\theta^\circ + .1327\,\theta^\circ + .0303\,\theta$$

$$= .4675\,\theta^\circ \text{ in minutes.}$$

which gives the equation for the change in slope at the top of the mast, when the ship is inclined θ° from the vertical.

The equation, $i = .4675\,\theta^\circ$ minutes, will give the error due to the slope of the mast, when the guns are fired with the ship in any position other than vertical. In practically all cases, the guns would not be fired at the instant the ship is more than 2° from the vertical position.

Assuming that firing did take place when the ship is 2° from the vertical, the error introduced would be 0.935 minutes, which is negligible.

Therefore, it may be stated that when firing with director fire, using the foretop director, the error introduced by the change of slope of the mast is negligible and need not be considered, as long as the position of the ship at the instant of firing, does not exceed 2° from the vertical position.

SECTION III

Range errors introduced into director firing by the motion of the gun during the firing interval.

Director firing is based on the principle that the gun is elevated to a fixed angle above the line of sight and that the projectile leaves the gun instantly in the predetermined direction when the line of sight crosses the point of aim. Since the line of sight must cross the point of aim, it is necessary that the ship be rolling. Therefore, it is impossible for the projectile to leave the gun in the desired direction since it does not leave the instant the line of sight crosses the point of aim. Some time being necessary for the pointer to press the firing key, the primer bridge to break, the powder charge to ignite and burn, and the projectile to travel down the bore of the gun. This time may be generally divided into two parts, first, the time from the instant the pointer wills to fire until the firing circuit is closed, and the time from the closing of the firing circuit until the projectile leaves the muzzle. The first of these is known as "the pointer's personnel time interval" and the second as "the time of ejection."

"The pointer's personnel time interval" is very small and for well trained men should be in the nature of a reflex action, for which the time is a few hundredths of a second. In fact, recent experiments at the Proving Grounds at Indian Head show that this time is about minus .045 seconds. The minus indicating that the pointer anticipates the crossing of the line of sight over the point of aim by that amount. Since the pointer's personnel "time interval" is a function of the man and is very small it has not been included in the following.

"The time of ejection" has been very carefully measured by the Bureau of Standards on the Brazilian Battleship "Sao Paulo", the "New Mexico" and other ships of the latest type. The average of one hundred fifty-five accurately measured times of ejection for the fourteen inch, fifty caliber guns of the "New Mexico" is eleven hundredths of a second. Of these times the shortest is .083 seconds and the longest is .157 seconds. Therefore in the following the time of ejection is taken as one-tenth of a second.

This time is very short and the angular velocity of roll during it may be considered constant. In the discussion of the effect of this time lag on the fall of shot in range, the following assumptions are made:

Effect of Ejection Time on the fall of Shot.

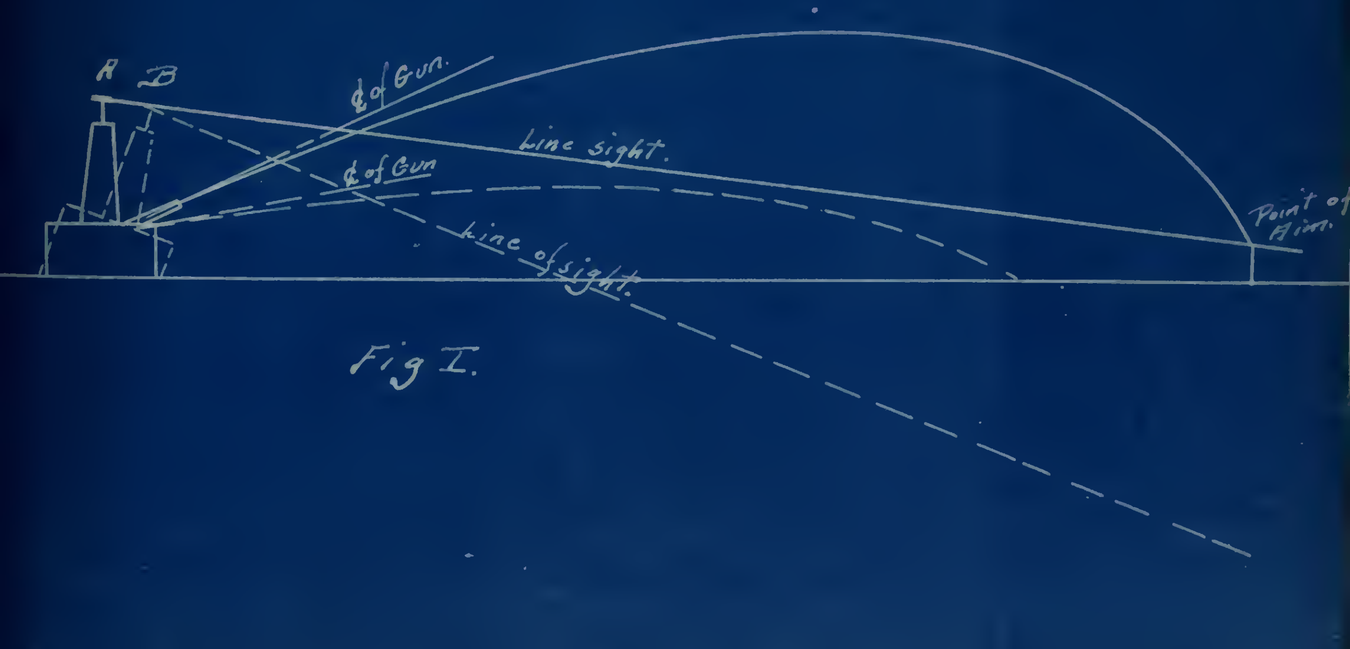


Fig I.

(1) That the line of sight is fixed in relation to the gun and that the angle between the line of sight and the center line of the gun remains constant.

(2) That the firing circuit is closed at the instant the line of sight crosses the point of aim.

(3) That the line of sight crosses the point of aim at the top of the roll, i.e., when the ship is on an even keel and rolling at the maximum angular velocity.

(4) That the gun remains at a fixed angle of train.

If the gun is trained abeam and the firing key is closed when the ship is in position A, Figure I as the line of sight crosses the top of the target and the ship is rolling toward the target with an angular velocity w minutes per second, it will be in position B when the projectile leaves the muzzle. That is, the ship will have rolled w t minutes towards the target. Therefore the projectile will leave the muzzle as if the gun were w t minutes lower than the correct angle of elevation, at which the gun was, when the firing key was closed, and the shot will fall short by the amount of range represented by a change of angle of elevation equal to w t minutes.

The above holds only when the gun is trained abeam. For any other position we will consider the

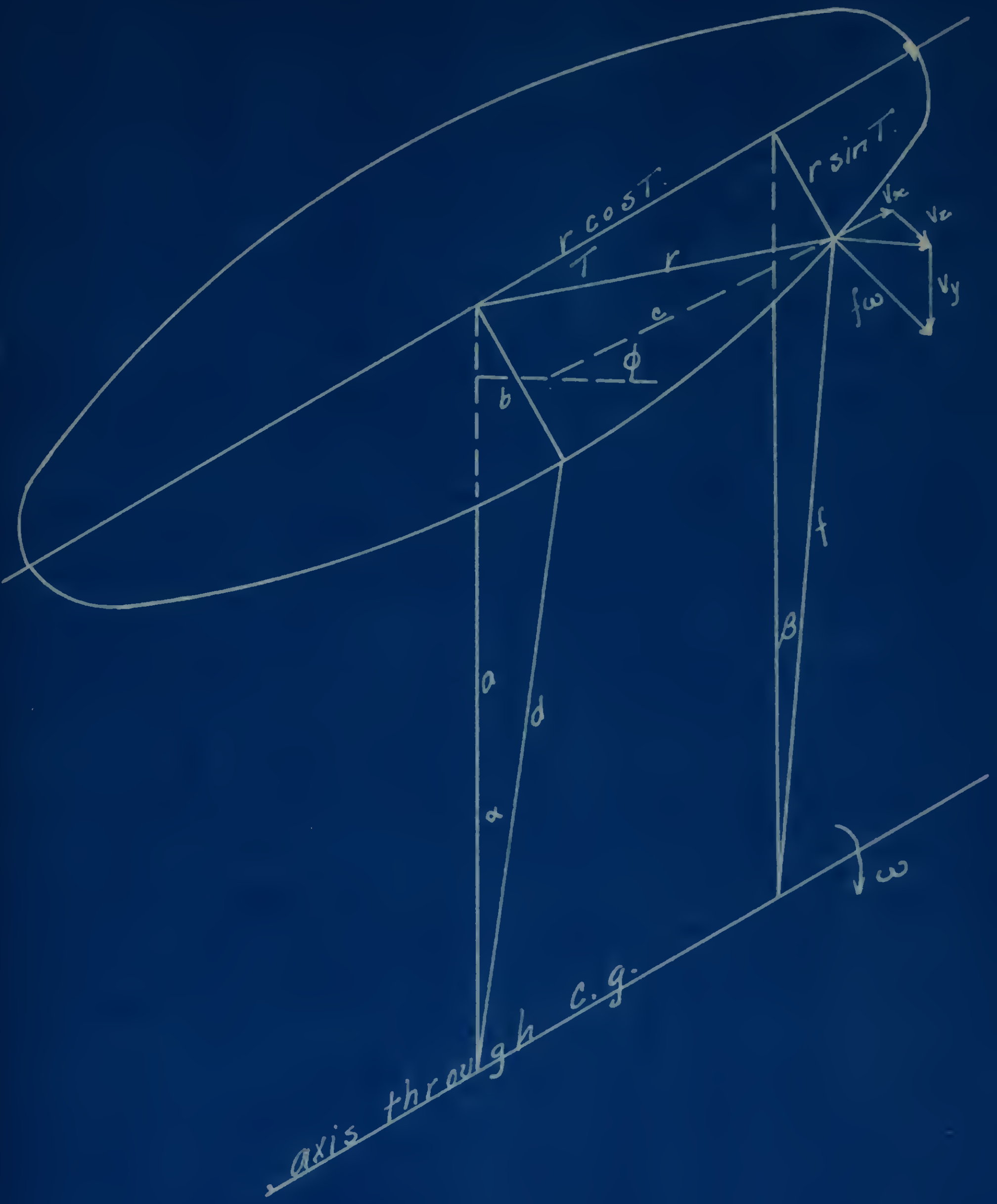


Fig II

circle in Fig. II. This circle, represent~~s~~ing the path of the muzzle of the gun for different angles of train, is rotating about a fixed horizontal line, to which one of its diameters is always parallel, and is at a distance "a" from the line in a direction perpendicular to the plane of the circle.

At the instant shown the plane of the circle is horizontal. At time t it will have tilted through an angle of t w minutes, and any point on the circumference will have moved a distance equal to t w r sin T away from the horizontal. Where r is the radius of the circle and T is the angle around to the right from the right-hand end of the diameter which is parallel to the axis of rotation. Therefore any radius will have tilted away from the horizontal by an angle whose sine is equal to,

$$\sin A = \frac{t\ w\ r \sin T}{r} = t\ w \sin T \qquad (1)$$

For small angles,

$$\sin A = A \qquad (2)$$

Therefore $A = t\ w \sin T.$ (3)

Since the gun lies in the same vertical plane as r, A is the angular error introduced for a time of ejection of t seconds for an angle of train T and can be taken from the range table and converted into yards of range.

The shot will fall over if the guns are fired on the up roll and short if fired on the down roll.

If we let,

θ = angle of roll from the vertical

θ_m = maximum angle of roll from the vertical

GM = the metacentric height of the ship.

ρ = the radius of gyration of the ship

g = the gravity constant = 32.16 ft.per sec.^{2}

t' = the time of a single roll, i.e. from θ_m on one side to θ_m on the other.

the angular acceleration for any ship is equal to,

$$\frac{d^2\theta}{d\,t^2} = -\frac{g\,G\,M}{\rho^2}\theta = -B^2\theta \qquad (4)$$

where B = a constant = $\frac{\sqrt{g\,G\,M}}{\rho}$ and depends on the constants of the ship.

Integrating (4) as follows:-

$$\int 2\frac{d\theta}{d\,t}\,\frac{d^2\theta}{d\,t^2}\,dt = -B^2\int 2\theta\,d\theta \qquad (5)$$

$$\left(\frac{d\theta}{d\,t}\right)^2 = -B^2\theta^2 + C \qquad (6)$$

Since at the end of the roll where $\theta = \theta_m$ the velocity equals zero,

$$C = B^2\theta_m^2 \qquad (7)$$

Therefore, $$\frac{d\,\theta}{d\,t} = B\sqrt{\theta_m^2 - \theta^2} = w \qquad (8)$$

Integrating this for t',

$$\int_0^{t'/2} d\,t = \frac{1}{B}\int_0^{\theta m} \frac{d\theta}{\sqrt{\theta m^2 - \theta^2}} \tag{9}$$

Therefore,

$$\frac{1}{2}\,t' = \frac{1}{B}\left[\sin^{-1} \# \cancel{x}\, \frac{\theta}{\theta m}\right]_0^{\theta m} = \frac{1}{B}\;\frac{\pi}{2} \tag{10}$$

Therefore,

$$t' = \frac{\pi}{B} = \frac{\pi\rho}{\sqrt{g\;G\;M}} \tag{11}$$

From the above,

$$w = B\sqrt{\theta m^2 - \theta^2} \tag{12}$$

and this becomes,

$$w = B\theta_m \tag{13}$$

when the ship is on an even keel and rolling at the maximum velocity.

Value of B can be taken from chart I for any ship for which the G.M. and ρ are known, or it can be calculated from (11) if the half period t' is known.

The above discussion is taken from works on Naval Architecture and is near the truth for the usual angles of roll. Also it has been prooved to hold by the photographic rolling data taken recently on the U.S.S. Nevada.

With this value of w (3) becomes,

$$A = t\;B\theta_m \sin T \tag{14}$$

and if we let t equal the time of ejection (14) becomes,

$$A = .1\;B\theta_m \sin T.$$

This has been done on charts II and III, for the U.S.S. North Dakota and the values of A in minutes are read on the left-hand scale on the middle vertical line. The methods of construction and use will be given later.

The above holds for either center line or broad side guns.

SECTION IV

Errors due to the motion of the ship imparting velocities to the projectile which tend to move it out of its calculated path.

By experiments in this country, England and Germany it has been proved that when a ship rolls she oscillates about a fore and aft axis which is very near to her center of gravity. This axis is not fixed but moves very slightly. This motion is small and in what follows the axis of oscillation will be considered fixed and passing through the center of gravity.

Figure III shows a plane through the center line of a gun and perpendicular to the axis of oscillation, with the gun trained abeam.

a = perpendicular distance from the axis to the horizontal plane through the trunnions of the gun.

b = the distance from the intersection of a with the horizontal plane through the trunnions, to the center of the trunnions.

c = the length of the gun from the center of the trunnions to the muzzle.

d = distance from the axis of oscillation to the muzzle of the gun.

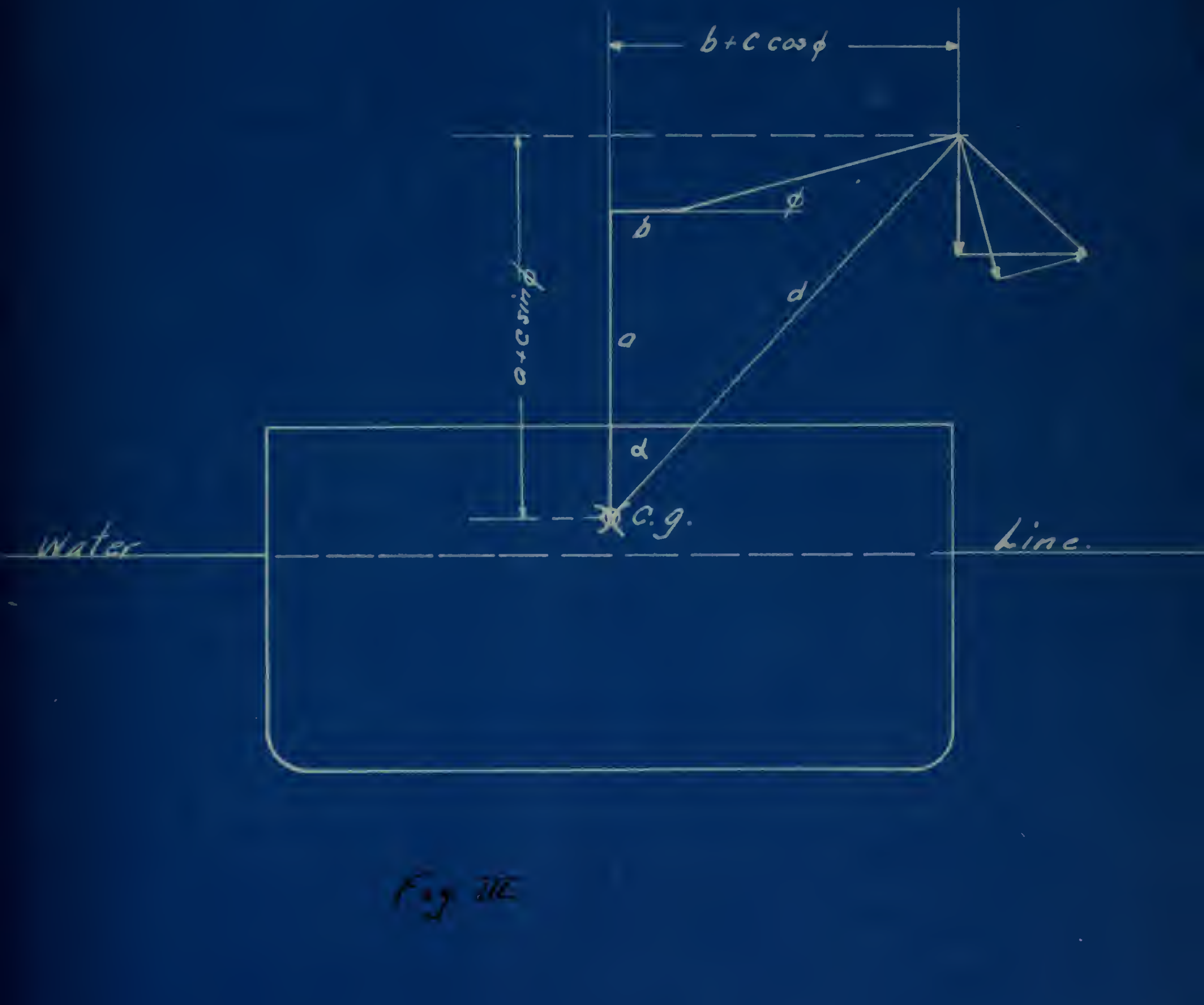


Fig. III

α = the angle between d and a

ϕ = angle ofelevation of the gun above the horizontal

If the ship is rolling with an angular velocity of w radians per second the muzzle of the gun will have a linear velocity of

$$V_m = d\ w \text{ feet per sec.} \qquad (1)$$

This velocity ~~v~~ will have components perpendicular to and along the path of the shell as it leaves the muzzle.

The component along the path will represent a slight change in muzzle velocity and is equal to,

$$V_t = V_m \cos (\alpha + \phi) \qquad (2)$$

This change is small and is not within the errors of the muzzle velocity.

The component perpendicular to the path is equal to,

$$V_p = V_m \sin (\alpha + \phi) \qquad (3)$$

This component is small, but since it acts perpendicular to the path of the projectile, it tends to throw it out of its path and the projectile will follow the direction of the resulting velocity. Therefore the shell does not leave the gun on a tangent to its calculated trajectory, but on a tangent to a trajectory which is above or below this trajectory, as if the angle of departure had been greater or less by the angle whose tangent is,

$$\frac{V_m \sin (\alpha + \phi)}{\text{muzzle velocity}} \qquad (4)$$

Center Line Gun.

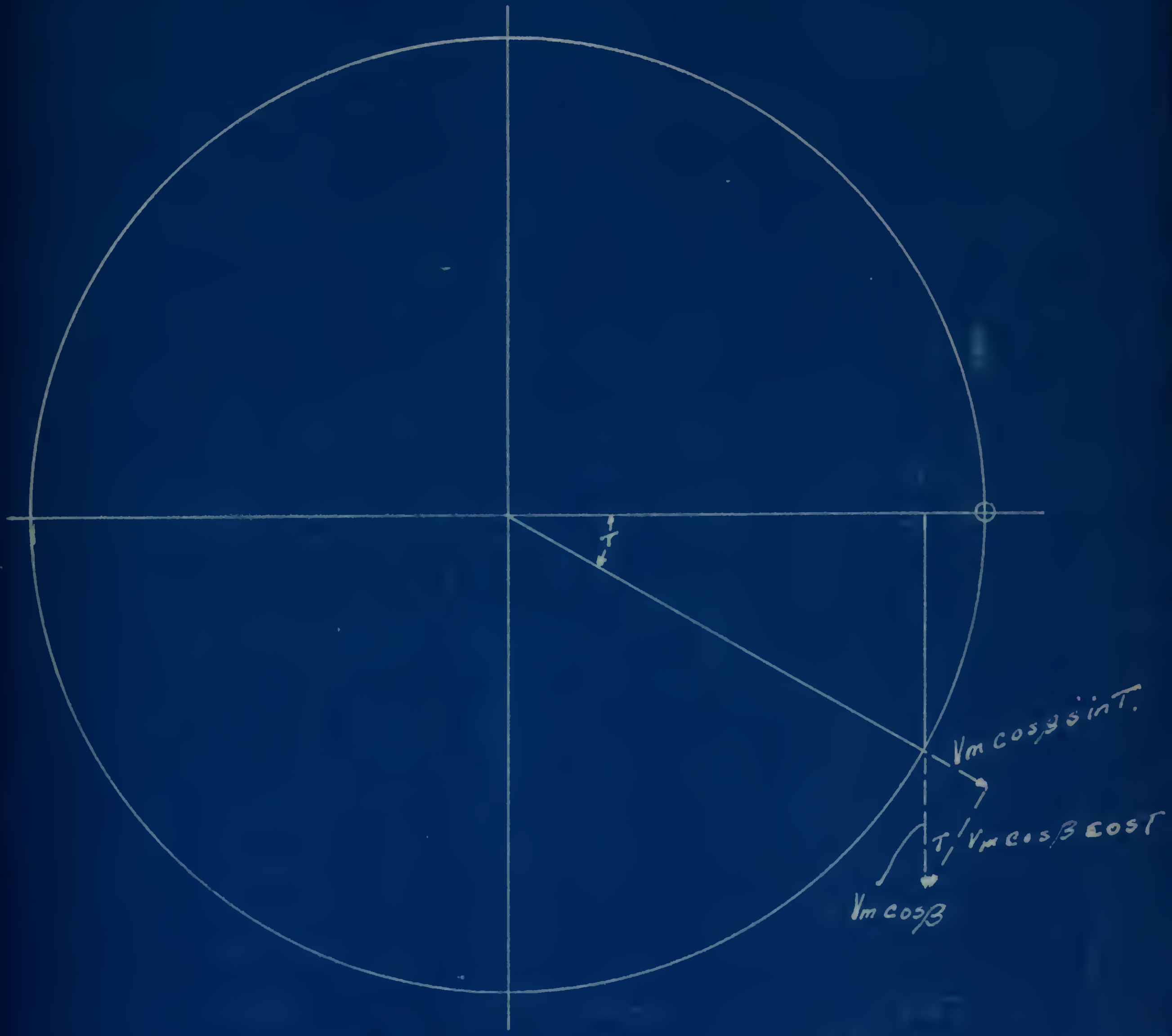


Fig 12

This correction can be calculated and added or subtracted either as angle or range in yards.

This velocity component would make the shots fall over if they were fired on the up roll and short if they were fired on the down roll.

The above applies to center line guns and to broad side guns so long as they are trained abeam, but for any other angle of train it does not hold.

The guns will now be divided into two classes: (1) Center line guns and (2) Guns which are not mounted on the center line.

Center Line Guns

Center line guns are guns which have their axis of train on the center line of the ship. In this class are turret guns, and the forward and after guns of destroyers.

The correction mentioned above is exact and is different for each turret or gun, since the distance d is different for each turret or gun.

Since it is assumed that the guns are to be fired in salvo and one correction is to be applied to all of them, some average correction must be found.

If we take vertical and horizontal components of V_m we have,

V_y = vertical component, = $V_m \sin\alpha$ (5)

and V_x = horizontal component = $V_m \cos\alpha$ (6)

V_y is approximately equal to V_p. The greatest error being at long range where this correction becomes so small as to be practically negligible. And the approximation becomes small at shorter ranges and smaller values of ϕ.

Since,

$$V_y = V_m \sin\alpha = d\,w\,\frac{(b + c\cos\phi)}{d} \qquad (7)$$

$$= w\,(b + C\cos\phi) \qquad (8)$$

If we let this equal,

$$V_y = w\,(b + c) \qquad (9)$$

we are very close for all angles of elevation and have a correction that applies to all guns.

If the guns are not trained abeam, the above does not apply.

From Fig. II it will be seen that for an angle of train T,

$$V_m = f\,w$$

where f is the perpendicular distance from the muzzle of the gun to the axis of oscillation. And V_m lies in the plane through the muzzle of the gun perpendicular to the axis of oscillation.

If we consider the ship on an even keel and let β be the angle between the vertical and f, we have

$$V_y = V_m \sin\beta = f\ w \sin\beta = f\ w \frac{(b + c \cos\phi)\sin T}{f} \qquad (11)$$

$$V_y = w\ (b + c \cos\phi)\ \sin T \qquad (12)$$

and

$$V_f = V_m \cos\beta \qquad (13)$$

where V_f is the horizontal component of velocity in the plane of f and β. This has components

V_x in the direction of the gun $= V_m \cos\beta \sin T$ (14)

$$V_x = f\ w\ \frac{(a + c \sin\phi)}{f} \sin T = w\ (a + c \sin\phi)\sin T \qquad (15)$$

and

V_z = perpendicular to the gun in a horizontal plane

$= V_m \cos\beta \cos T$ (Fig. IV) (16)

$$= f\ w\ \frac{(a + c \sin\phi)}{f} \cos T = w(a + c \sin\phi)\cos T \qquad (17)$$

V_z does not affect the range, but affects deflection.

If in (12) we let

$$V_y = w\ (b + c)\ \sin T \qquad (18)$$

we have a correction for all guns and very nearly correct.

Since $w = B\theta_m$ for our assumed conditions, (18) becomes,

$$V_y = B(b + c)\theta_m \sin T \qquad (19)$$

in which B and (b + c) are constants.

This equation is in the same form as that of Section III and it can be charted on the same chart, using θ_m and T as arguments.

This has been done on Chart II and is the right-hand scale on the middle vertical line.

Guns Not on the Center Line.

Guns not on the center line, such as the torpedo defense batteries of battleships and waist guns of destroyers, are assumed to have their axis of train at the trunnions and that these axes is a fixed distance from the center line. This is illustrated in Fig. V.

Using the same notation in this case:-

$$V_m = f\,w \qquad (20)$$

$$V_y = V_m \sin\beta \qquad (21)$$

$$V_f = V_m \cos\beta \qquad (22)$$

$$V_x = V_f \sin T = V_m \cos\beta \sin T \qquad (23)$$

$$V_z = V_f \cos T = V_m \cos\beta \sin T \qquad (24)$$

But now $$\sin\beta = \frac{b + c\cos\phi \sin T}{f} \qquad (25)$$

and $$\cos\beta = \frac{a + c\sin\phi}{f} \qquad (26)$$

since b is fixed.

Therefore,

$$V_y = f\,w\,\frac{b + c\cos\phi \sin T}{f} = w\,(b + c\cos\phi \sin T) \qquad (27)$$

$$V_x = f\,w\,\frac{a + c\sin\phi}{f}\sin T = (a + c\sin\phi)\,w\sin T \qquad (28)$$

$$V_z = f\,w\,\frac{a + c\sin\phi}{f}\cos T = (a + c\sin\phi)\,w\cos T \qquad (29)$$

Using (27) as before and letting $c\cos\phi = C$ and putting $w = B\,\theta_m$ we have,

$$V_y = b\,B\,\theta_m + c\,B\,\theta_m \sin T \qquad (30)$$

Broadside Gun.

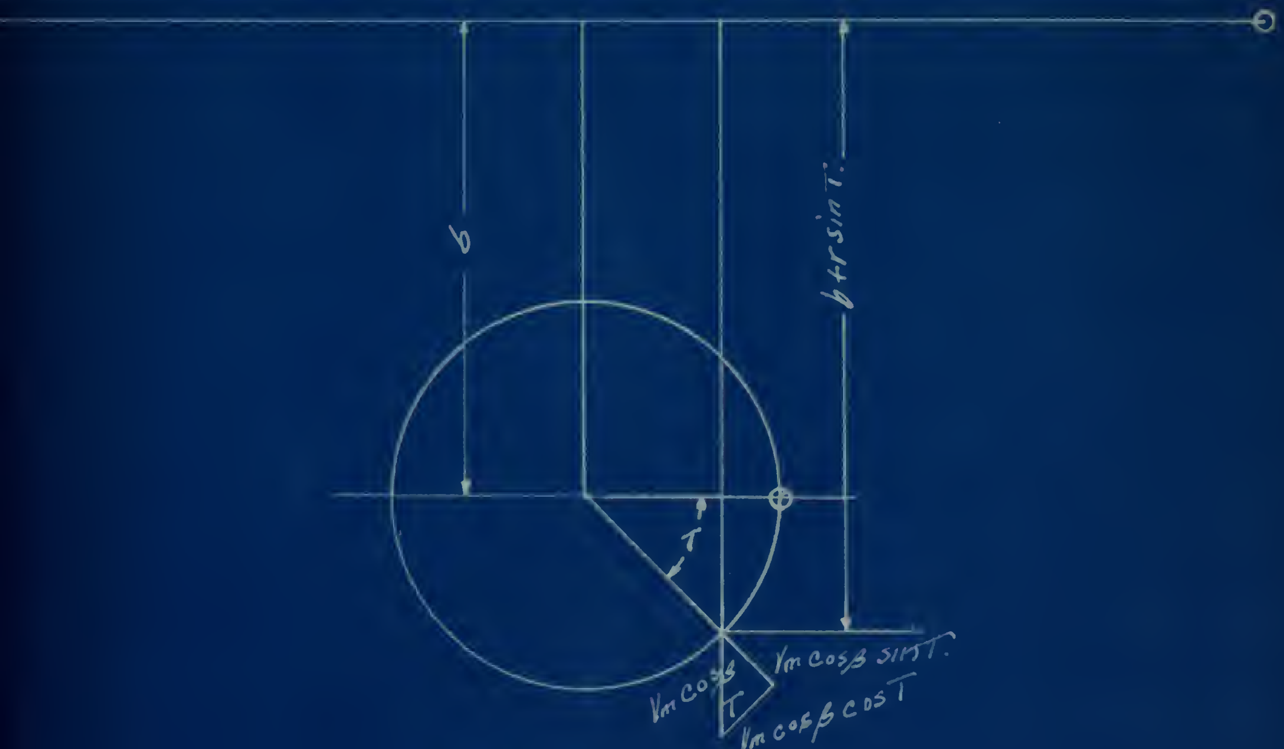


Fig II

From this we have,

$$V_{y1} = b\,B\,\theta_m \tag{31}$$

and

$$V_{y2} = c\,B\,\theta_m \sin T. \tag{32}$$

(32) is in the same form as (19) and can be charted in the same way. While (31) can be charted on the same line as θ_m. This has been done on Chart III.

SECTION V

Charts II and III. Method of Construction and Proposed Use.

These charts are constructed from the formulae deduced in Sections III and IV, by the methods given in "Graphical and Mechanical Computations" by Lipka, page 45.

Chart II is constructed from the equations,

$$A = .1B\,\theta_m \sin T$$

$$\text{and} \quad V_y = B(b+c)\,\theta_m \sin T$$

The first of these may be written,

$$\log A = \log .1 + \log B + \log \theta_m + \log \sin T$$

θ_m is laid off on the right hand scale in radians from .0175 which equals 1 degree to .2618 which equals 15°, by means of a logarithmic scale and the points are marked in degrees. The modulus used is 10 on the original chart.

Sin T is laid off on the left hand scale for the natural sine of angle from 5 degrees to 90 degrees and marked in degrees. The modulus used is 10 on the original chart.

The modulus for A is therefore 5 and the scale comes mid way between θ_m and T. A was calculated for each degree of θ_m with T at 90 degrees and checked for two other readings of T.

The angle for V_y for each degree of θ_m for T equal to 90 degrees was then calculated and plotted on the

chart. This was also checked for two other values ofT.

The range correction curve was then drawn by taking the difference in the angle of departure for one hundred yards from the range table and calculating the correction for one minute.

The purpose of this chart is to give a ballistic correction for the roll. The maximum angle from the vertical is taken by the rolling battens, the angle of train is known and these two points are connected by a straight edge. The readings on the center scales are added together and the sum is multiplied by the correction per minute as taken from the range curve for the approximate opening range, or the sum of the readings is the correction in minutes.

This is a minus correction if firing on the up roll and plus if firing on the down roll.

Chart III is constructed in the same manner as Chart II, except the V_y correction is divided into two parts, since it is for the broad side guns. The first part,

$$V_{1y} = b\ B\theta_m$$

is plotted on the same scale as θ_m and the second part,

$$V_{2y} = c \sin T\ B\theta_m$$

is plotted in the same manner as V_y on Chart II.

As constructed and before photostating these charts had the accuracy of a ten inch slide rule.

If we are given the problem to find the ballistic correction for roll for the 12" guns of the U.S.S. North Dakota firing at 300° train rolling 5° from the vertical, range 10,000 yards with the ship rolling down.

The shortest time of ejection is .09 seconds and the longest .12 seconds. Find the dispersion caused by the roll.

Solution:

Connecting 5 on the right hand scale with 300 on the left hand scale we get 12 and 1.9 minutes on the center scales. Therefore, correction in minutes is 12 + 1.9 or 13.9 minutes plus.

From the range correction curve for 10,000 yards the reading is 26. Therefore, the range correction is 13.9 times 26, or 361.4 yards plus.

For dispersion the difference in time of ejections is .12 - .09 = .03. Therefore the angular dispersion is,

$$12 \cdot \frac{.03}{.10} \text{ or } 12 \times .3 = 3.6 \text{ minutes}$$

and in yards is equal to 26 x 3.6 = 93.6 yards.

SECTION VI

Description of the test on the masts of the U. S. S. North Dakota, and the analysis of the results obtained therefrom.

The object of this test was to determine the suitability of the cage mast as a Director Station, and also to determine the error if any, when using director fire, the ship rolling in a seaway.

The general method of the test was to load the mast at the top, in such a way as to simulate as nearly as possible by static forces, the dynamic and static forces that are set up by the weights on the mast when the ship is rolling, and to measure the deflection and change in slope, of the mast caused by these forces.

These masts are of the usual basket construction. The Foremast which is 81 feet 4 inches between bottom and top base rings, is made up of 48 elements for a height of 56.7 feet, and of 24 elements from a height of 56.7 feet to the top. Each element is straight between the foundation and the top ring, and makes an angle of approximately 15° with the vertical elements going alternately to right

and left. From the base ring to a height of 14.75 feet, the elements are 2 1/2 inches outside diameter, 2 1/4 inches inside diameter, brass tubing. From 14.75 feet to 29.78 feet, the elements are 1 3/4 inches outside diameter, 1 1/2 inches inside diameter brass tubing. Above 29.78 feet the elements are 1 3/4 inches outside diameter and 1 1/2 inches inside diameter, steel tubing. At the base ring and top rings the elements are riveted to a casting, which in turn is riveted to the flange of the channel beam forming the foundation. Wherever the elements cross, they are fastened together with a casting and bolts. At approximately every six feet, rings are fitted, inside and out, to keep the mast in its proper shape. Thus it may be seen that the mast is practically made up of a series of circular Warran Trusses, whose diagonals make an angle of 15° with the vertical.

The mast carries a search light platform with four searchlights, and in addition it carries the top, which is used as a control station. The bridge structures are supposed to be supported by the deck, and to contribute nothing to the load on the mast.

The mainmast is similar to the foremast except that it has a height of 96 feet, and consequently a larger diameter at its base.

By construction, the mast is supposed to be symmetrical and its motion unrestricted in all directions. Since the ship was afloat, in order to reduce the possibility of errors, it was necessary that all instruments be on the ship while taking measurements. For the same reason, any force applied to the mast from an external source would tend to move the ship, it was decided to load the mast on the ship, in a fore and aft direction.

For loading the mast a 7/8 inch steel cable was passed from the foremast to the mainmast, and was made fast to a 14 inch 7/8" turnbuckle. This turnbuckle was made fast to the after side of the top ring foundation by a steel wire strap which was passed through the after lightening holes. The position of the turnbuckle was so adjusted that it could be operated by a man standing on the ladder immediately under the top.

In the foremast the cable was made fast to a lever arm 3 inches from the Fulcrum. The fulcrum was secured to the top base ring by a steel strap passed through the two forward lightening holes. Thirty-three inches from the fulcrum was secured a small tackle, which in turn was made fast to a 500 pound spring balance, which was secured to the forward elements of the mast. The

lever arm carried a knife edge at these three points.

For applying the load the turnbuckle was set up, and the tackle in the foremast was adjusted so as to keep the lever arm vertical. By this means the load was assumed to be applied at the top ring of the mast and was equal to eleven times the reading of the 500 pound spring balance. The cable was run so as to be as near as possible over the center line of the ship.

In each top, a gunner's quadrant was placed on the base plate of each directorscope, in a fore and aft line. The scales of these quadrants can be read within 10 seconds of arc. This was the smallest increment used, for while smaller increments could be estimated, it was not attempted due to a slight pitching of the ship, estimated to be about 5 seconds of arc.

Scales, which were marked in 1/16 of an ~~arc~~ inch, were secured to spars, which were rigged in the mainmast at the height of 40'6", 68', 1 1/2" and under the top, height 96'2" from the bottom foundation. On the foremast, one scale only was rigged which was secured to the top near the upper ring. A surveyor's transit was placed in the port anti aircraft gun platform in such a way that the three scales on the main-

mast could be read directly. Another transit was placed on the starboard side of the Signal bridge with which to read the scale on the foremast. Readings of these scales could be made accurately to 1/32 inch.

It is assumed that the deflection of the mast would not be large enough to affect the accuracy of the transit readings, and that these readings would represent the true deflection of the mast, and also that the transits not being supported by the mast would not be affected by the deflection of the mast.

To check the readings of the transits, a steel tape was run between the tops. This tape was loaded by a spring balance to 60 pounds and measurements taken between two fixed points on the mast, but due to the wind pressure on the tape, the readings of this tape were not considered sufficiently accurate for use.

Plumb-bobs were dropped from the end of each spar in the mainmast, with the idea of reading the deflection from these, but the wind made their use impossible.

Using this apparatus as described above two runs were made, one in the forenoon and one in the afternoon of Friday, May 11th, 1923.

In the first run before any load was applied,

Zero readings of the scales on the mainmast were carefully taken and the upper scale was watched while the lever arm was pulled down from a horizontal to a vertical position. This force, approximately 1200 pounds, was sufficient to cause a movement of the top of the mainmast of 8/16 of an inch, and showing a change of reading on the gunner's quadrant of 40 seconds. This movement shows up clearly on the plot of the Load-Deflection curve for run #1. The load was then applied in increments of approximately 500 pounds up to about 4500 pounds. Readings were taken at 1000 pound increments as the load was decreased. All instruments were read for each load applied. Readings for the foretop scale were lost for this run, due to the fact that the transit was struck, and moved during the run.

For both runs, the load-linear deflection, and load-change of slope curves plot as straight lines for both the foremast and the mainmast. For the foremast the load-change of slope curve shows that a load of about 550 pounds was applied before there was any change of slope. This shows that the first movement of the base of the directorscope was in a horizontal plane or in other words, that the mast acted as a pantagraph up to this load. Beyond this load, the action

was the same as for a beam, change in slope accompanying a change in deflection, the loading rate being 1175 pounds, per minute of arc.

For the mainmast the load-deflection curve shows that there was an initial horizontal movement of the mast of 13/64" without load, or in other words there was this amount of lost motion in the mast structure which was necessary to take up before the mast itself offered any resistance to the force. For the mainmast the loading rate is 2000 pounds per minute of arc, and 4900 pounds per inch of deflection.

At the completion of the first run, the turnbuckle was slacked off, the lever arm allowed to take a horizontal direction in order to remove all strain from the mast, but all the curves for the second run show an initial load of approximately 500 pounds. Otherwise the curves are identical with the previous run, and the constants given are the same.

For this run, the deflections for the foremast are believed to be accurate and show the loading rate to be approximately 6400 pounds per inch deflection.

In the light of the above data, the following conclusions are arrived at:-

(1) That the masts have a small amount of lost motion, and while this is being taken up the mast acts as a pantagraph with no change in slope at the top.

(2) That after this lost motion is taken up, the mast acts like a stiff cantilever beam.

(3) That the constants for these masts are:-

Mainmast	Foremast
2000 lbs/min.arc	1175 lbs./min.arc
5000 lbs/in.deflection	6400 lbs./in.deflection

(4) Upon releasing the load the mast returns to the position it occupied after the lost motion was taken up.

Authors' Note:

Before the load was applied, it was possible to shake the entire mast by one man shaking the hand rails in the tops. While applying the load the mast was very rigid both fore and aft and athwart ships.

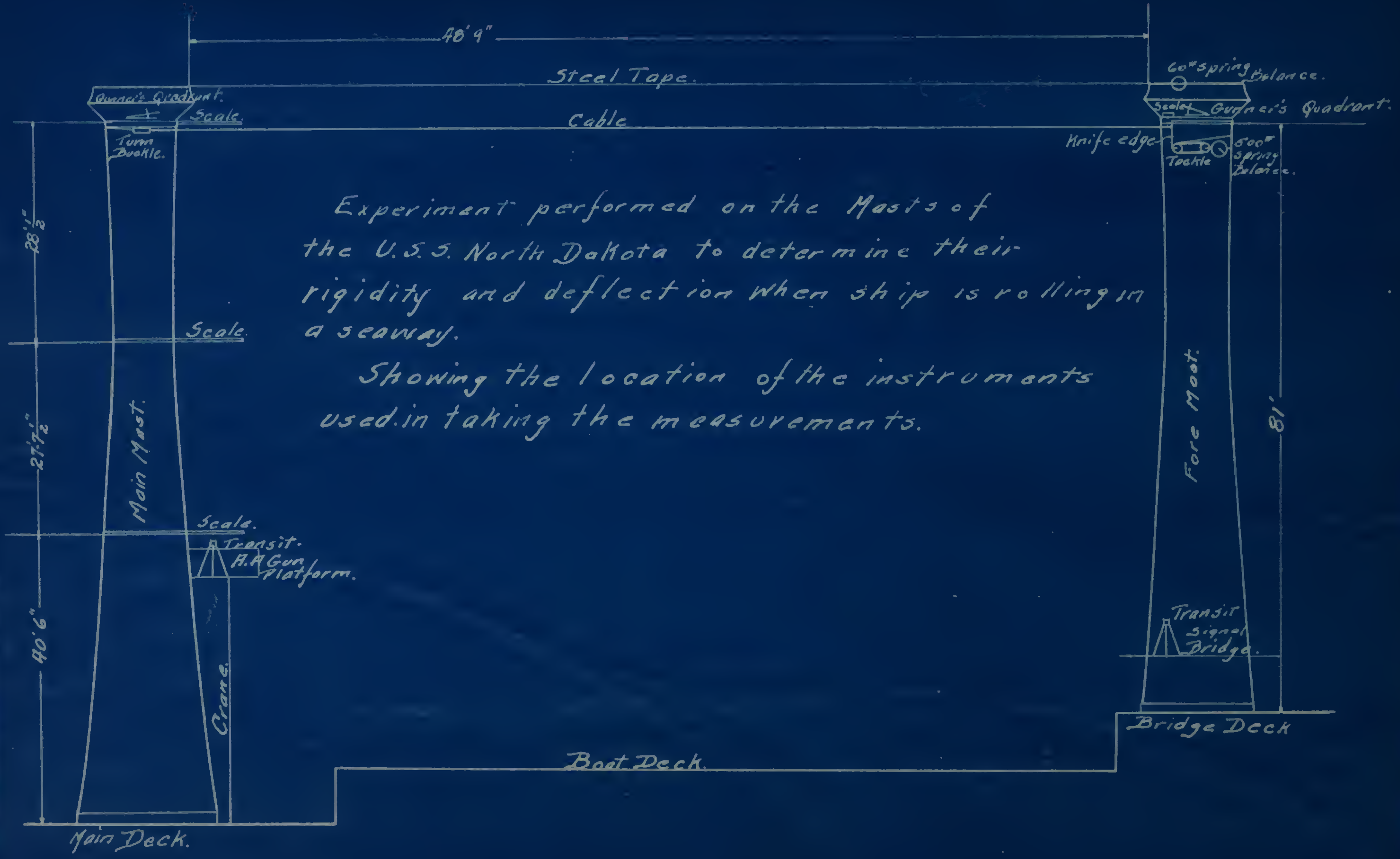
DATA

RUN #1

Load	Fore Top Transit	Fore Top Gunner's Quadrant	Main Transit	Top Quadrant	Reading No.
0	0	0	0	0	(1)
1325.5	1/16	0'40"	8/16	0-40	(2)
1578.5	3/16	1-00	9/16	0-50	(3)
1694	5/16	1-00	9/16	0-50	(4)
2354	9/16	1-50	10/16	1-00	(5)
2805	13/16	2-20	12/16	1-20	(6)
3300	19/16	2-30	14/16	1-50	(7)
3773	---	3-00	15 1/16	1-50	(8)
4367	---	3-20	4 18/16	2-10	(9)
3311	---	2-20	14/16	1-10	(10)
2233	---	1-30	10/16	0-50	(11)
0		0-20	5/16	0-10	(12)

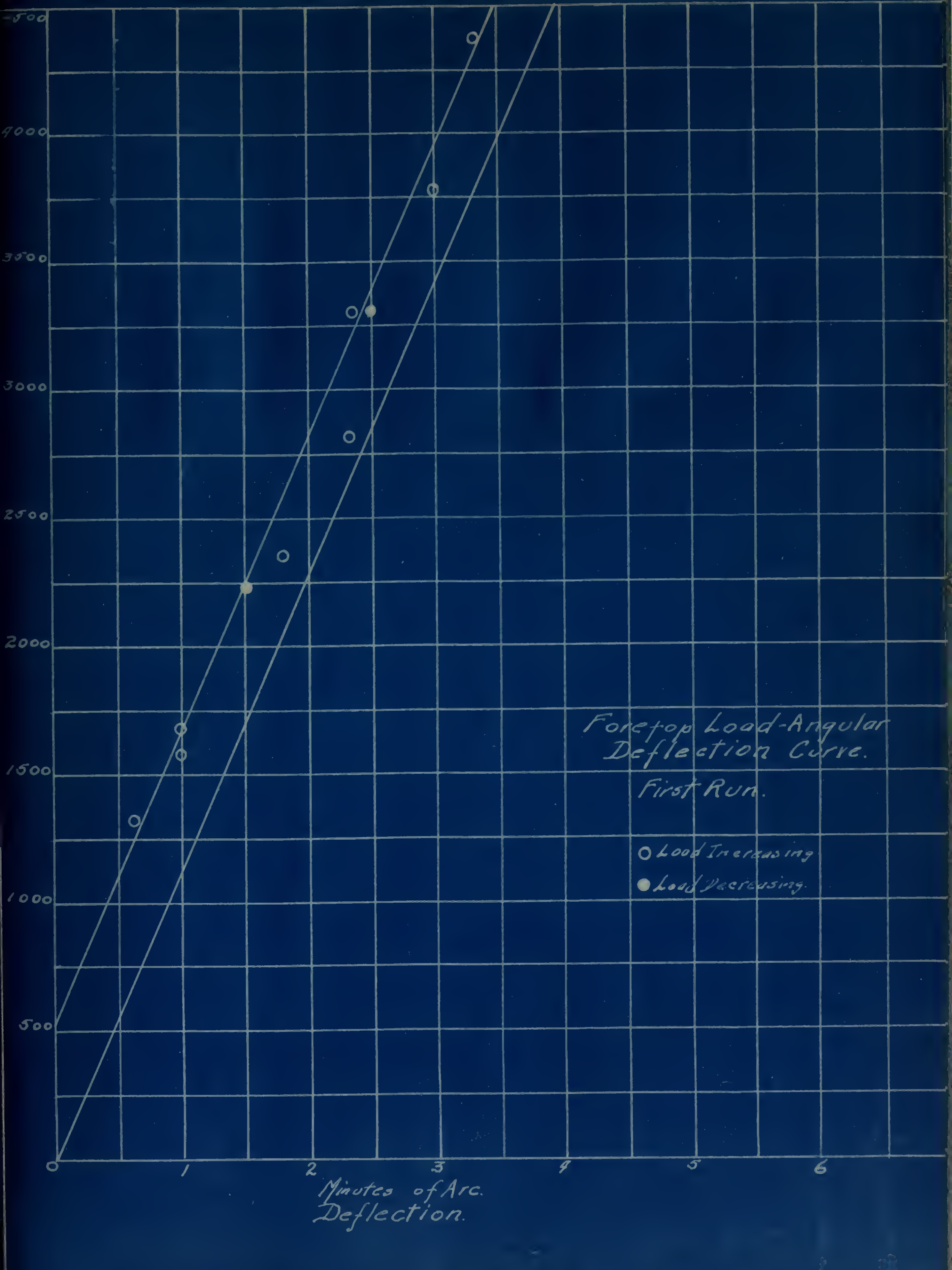
RUN #2

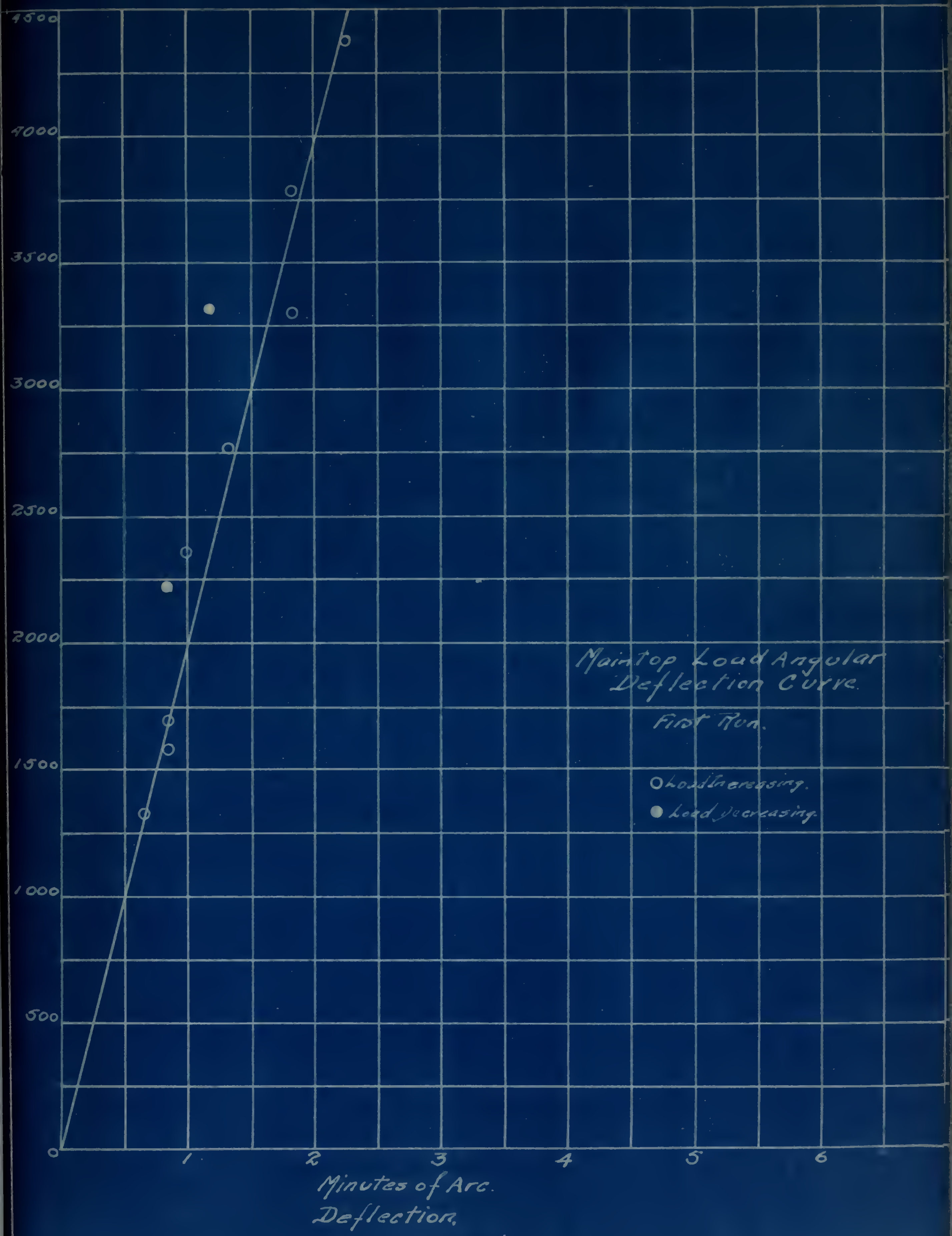
0	0	0	0	0	(1)
1199	1/16	0-20	2/16	0-10	(2)
2156	4/16	1-20	6/16	0-40	(3)
2948	6/16	2-10	7/16	0-50	(4)
3289	7/16	2-50	9/16	1-20	(5)
3961	8/16	3-10	11/16	1-30	(6)
3894	8/16	3-10	11.25/16	1-30	(7)
3234	6/16	2-30	9.5/16	1-00	(8)
2233	4/16	1-20	6/16	0-50	(9)
1067	1/16	0-40	3/16	0-40	(10)
0	- 1/16	0-10	0	0-30	(11)

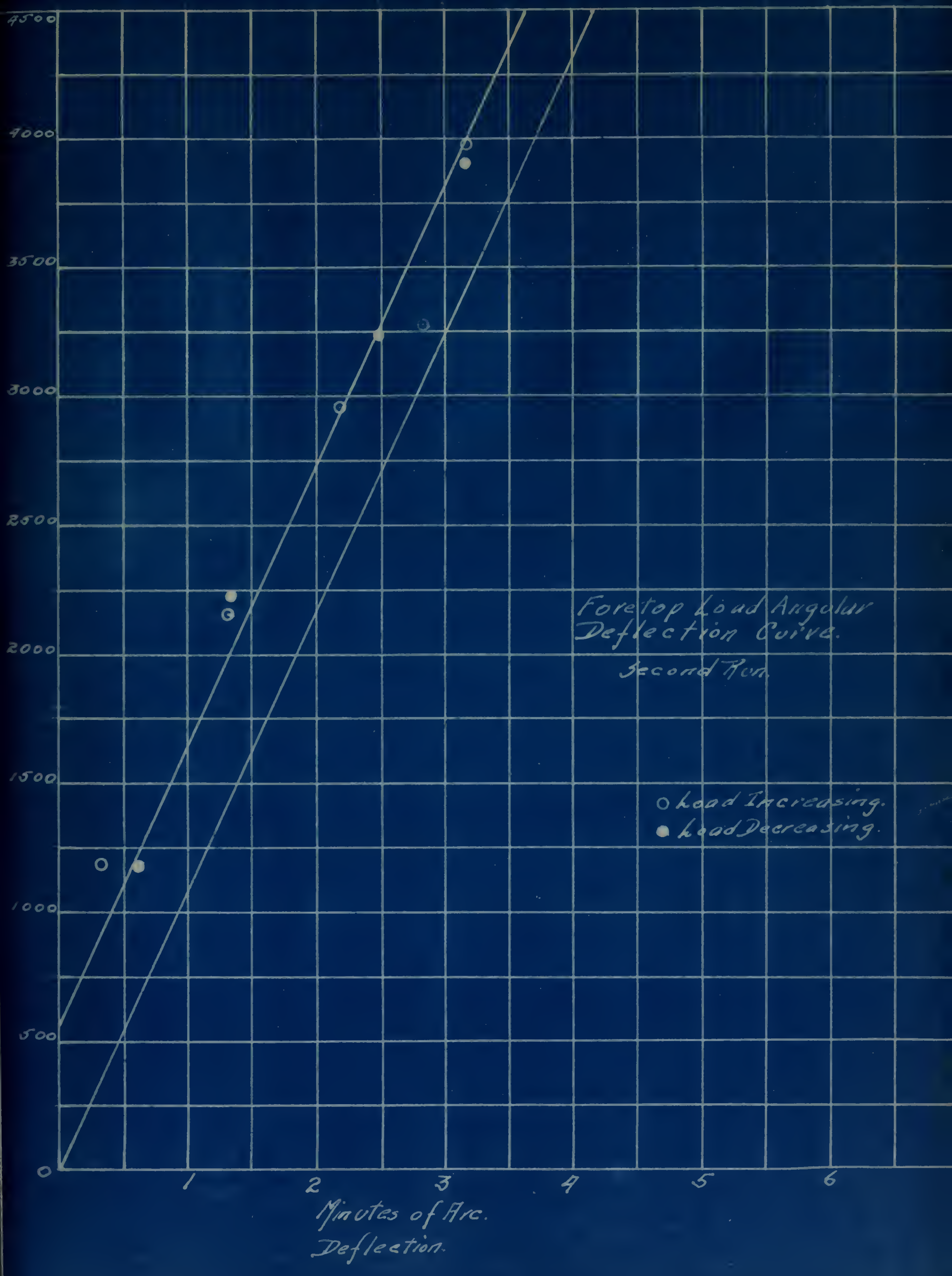


Experiment performed on the Masts of the U.S.S. North Dakota to determine their rigidity and deflection when ship is rolling in a seaway.

Showing the location of the instruments used in taking the measurements.

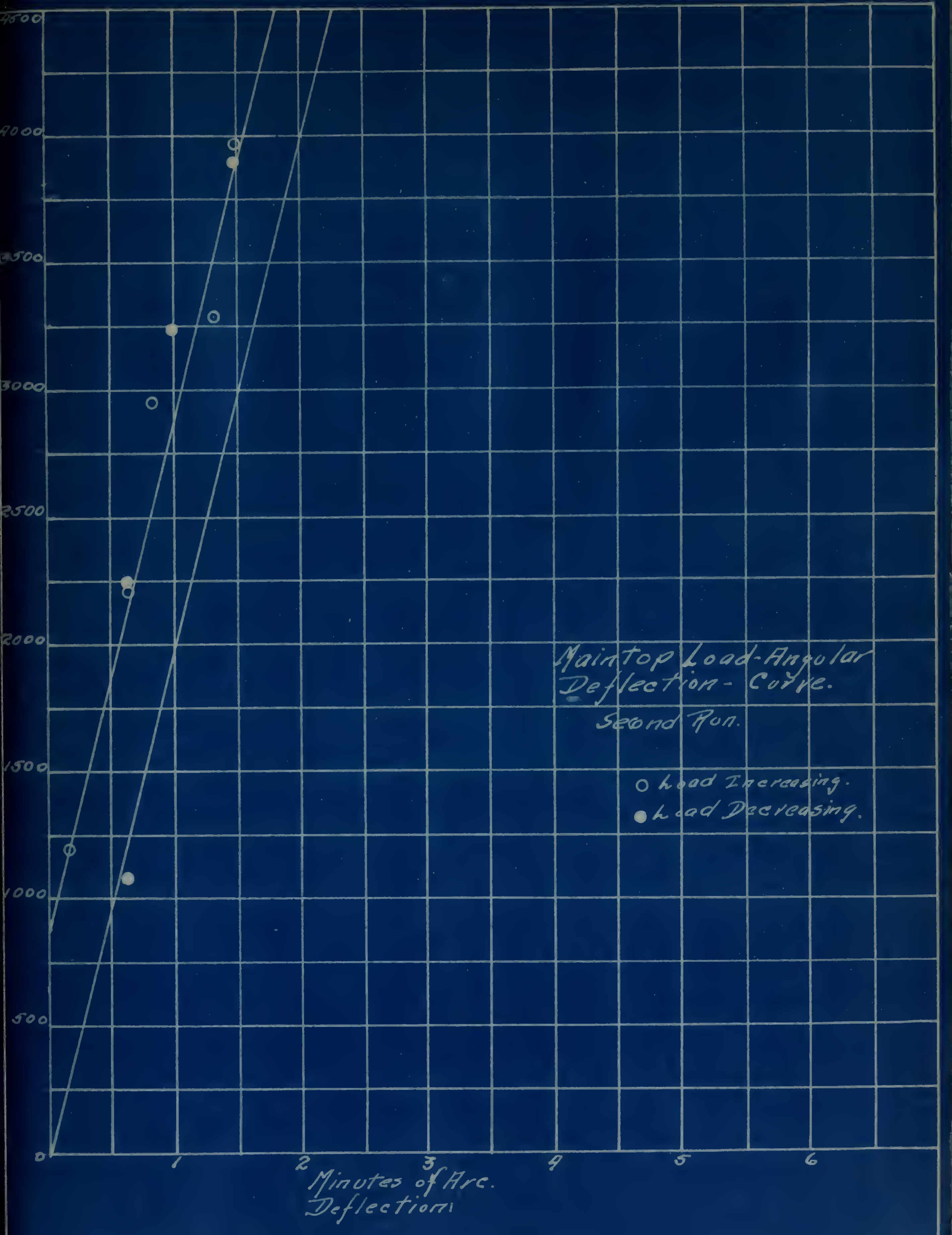

Foretop Load-Angular Deflection Curve.
First Run.
○ Load Increasing.
● Load Decreasing.
4000
3500
3000
2500
2000
1500
1000
500
0
1
2
3
4
5
6
Minutes of Arc.
Deflection.


4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
2
3
4
5
6
Minutes of Arc.
Deflection.
Maintop Load Angular
Deflection Curve.
First Run.
○ Load Increasing.
● Load Decreasing.



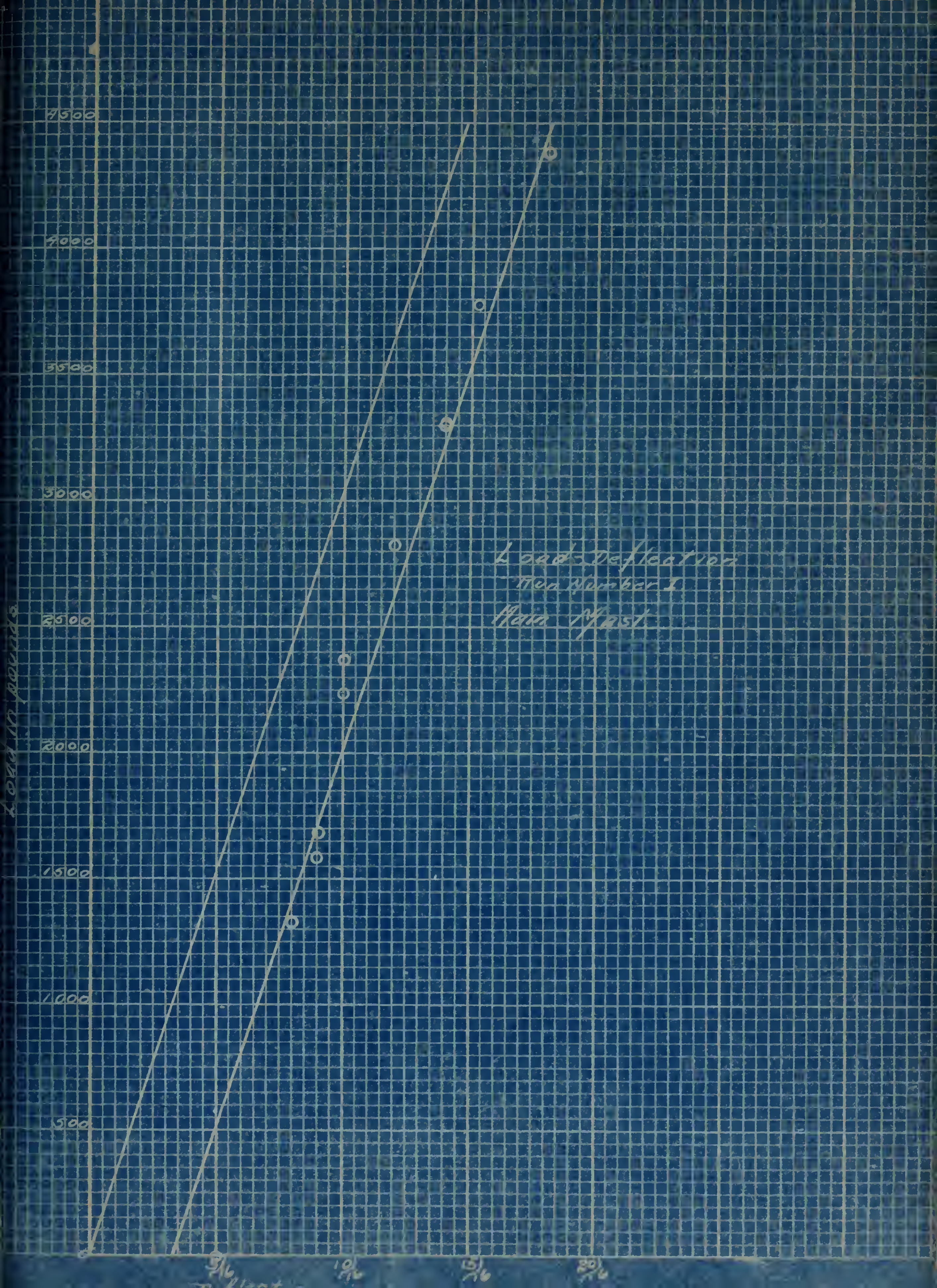
Foretop Load Angular Deflection Curve.

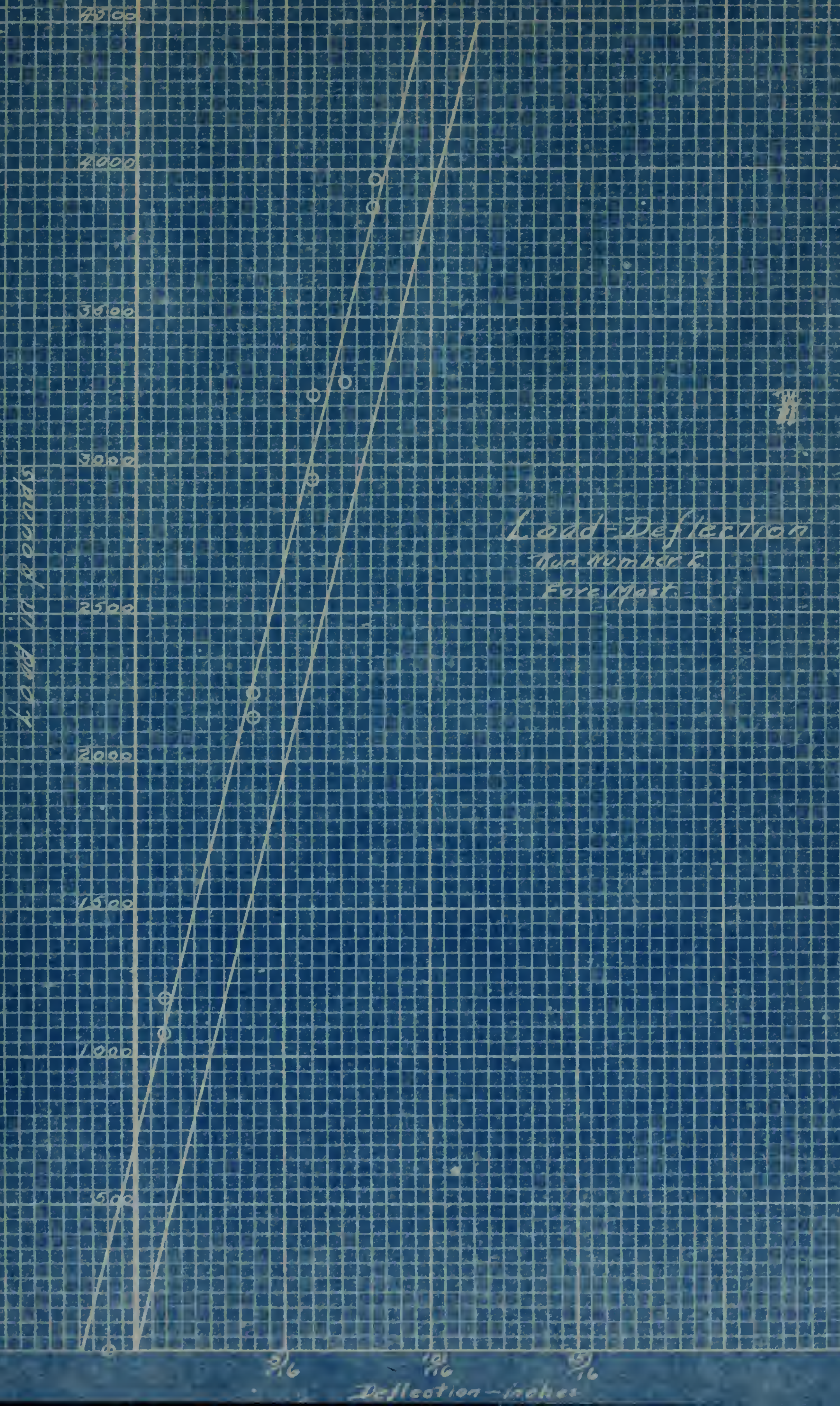
Second Run.

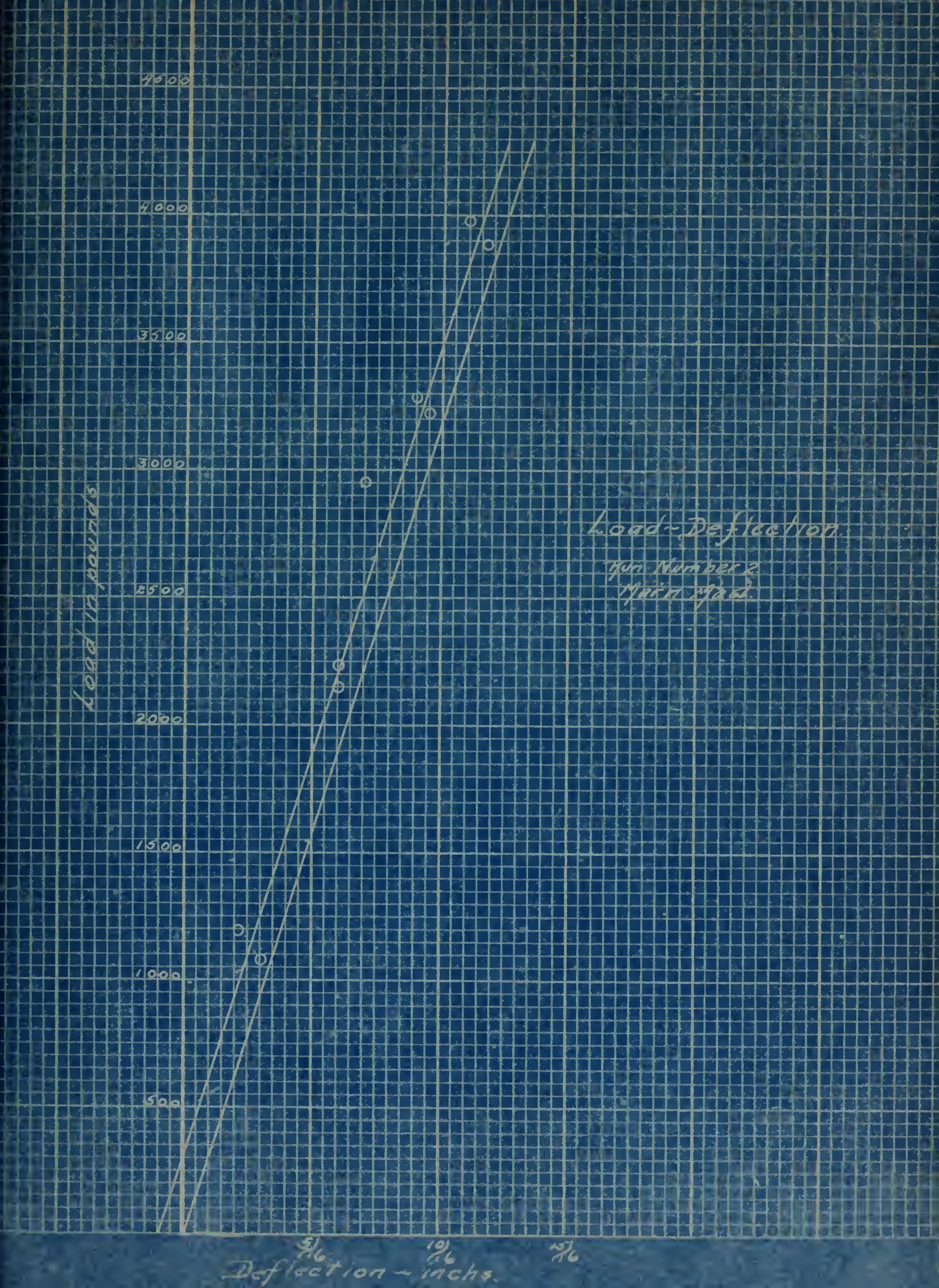


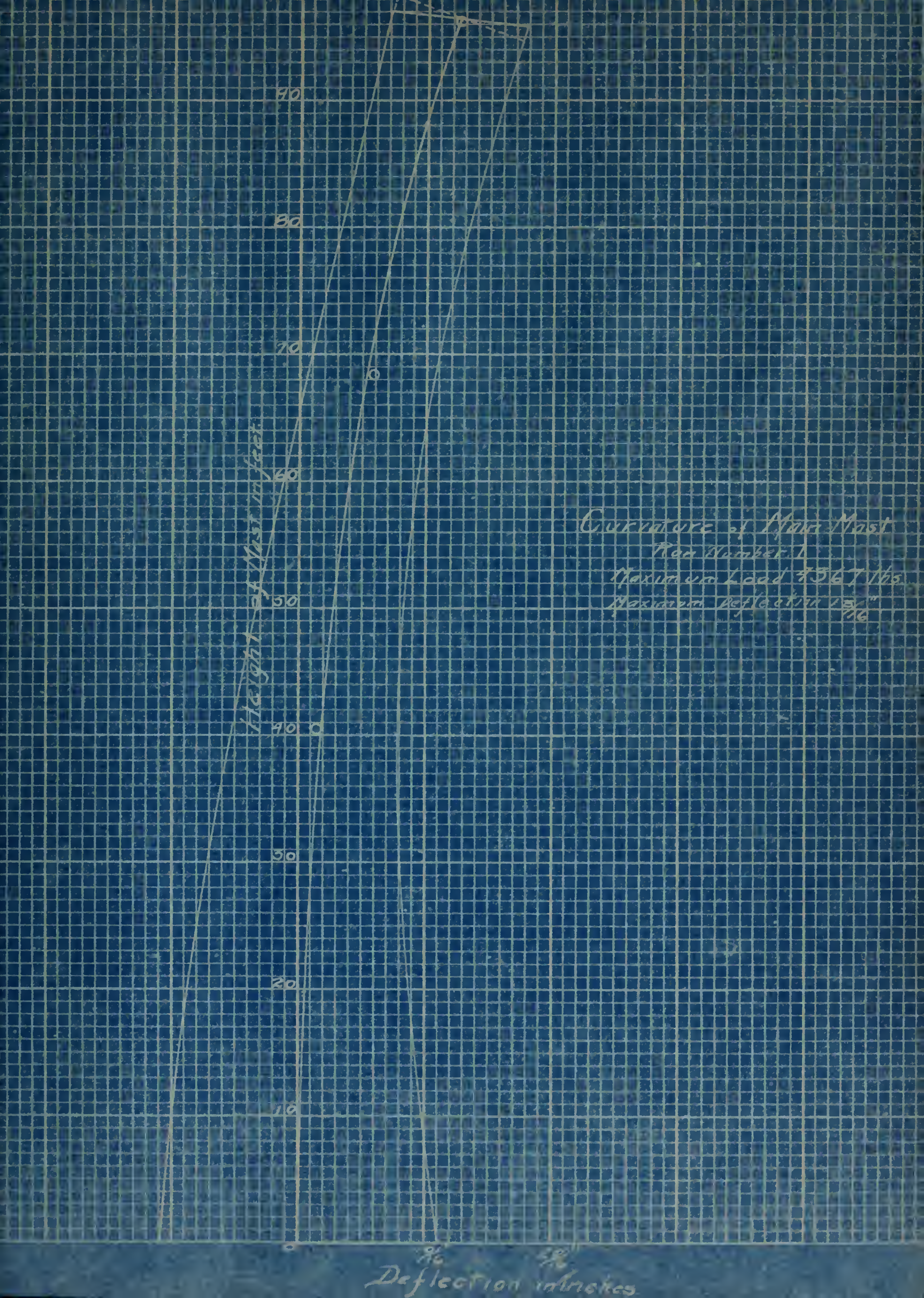
Maintop Load-Angular Deflection-Curve.

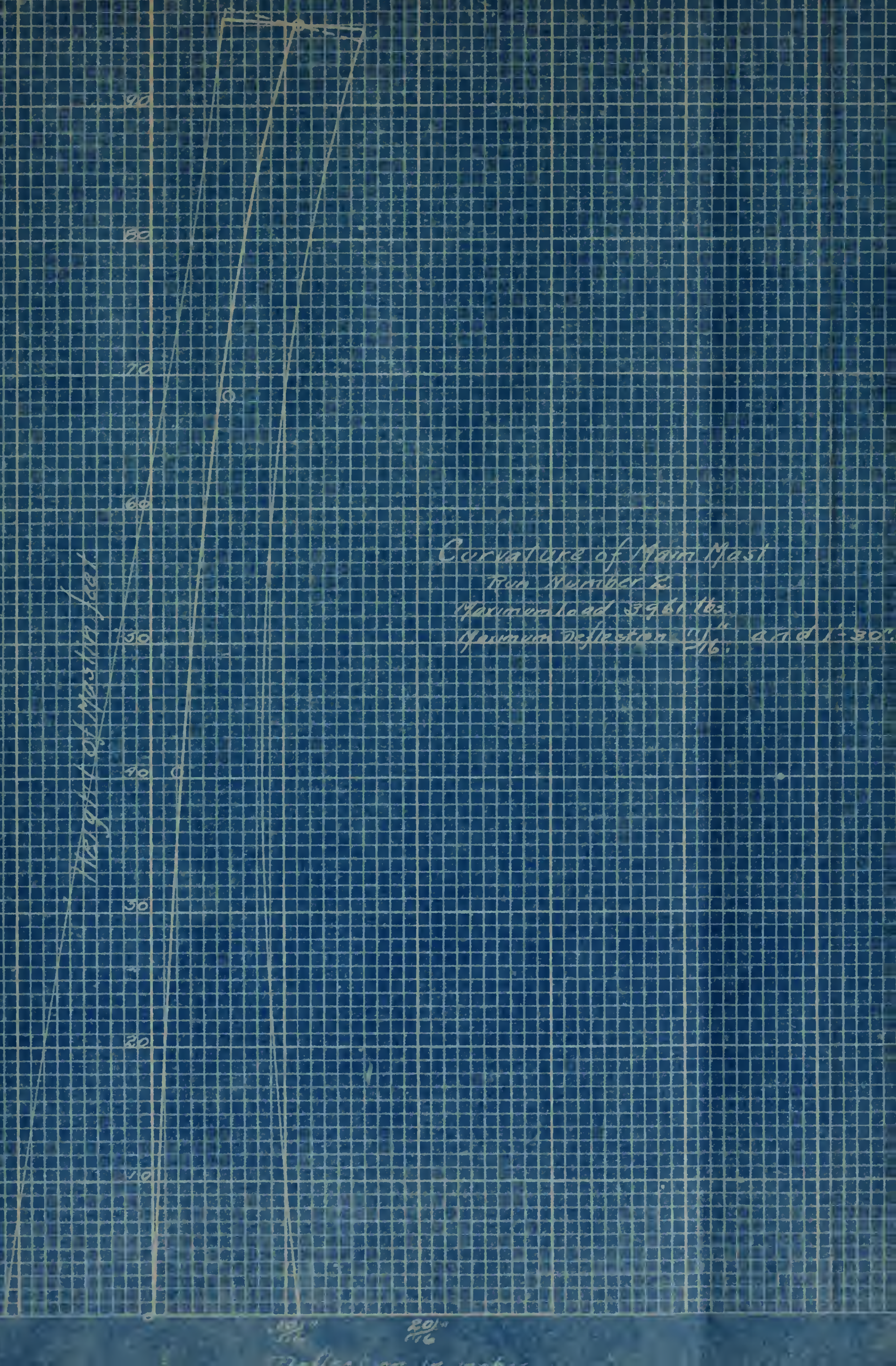
Second Run.


Load Deflection
Run Number 1
Main Mast
Load in pounds
4500
4000
3500
3000
2500
2000
1500
1000
500
5/16
10/16
15/16
20/16

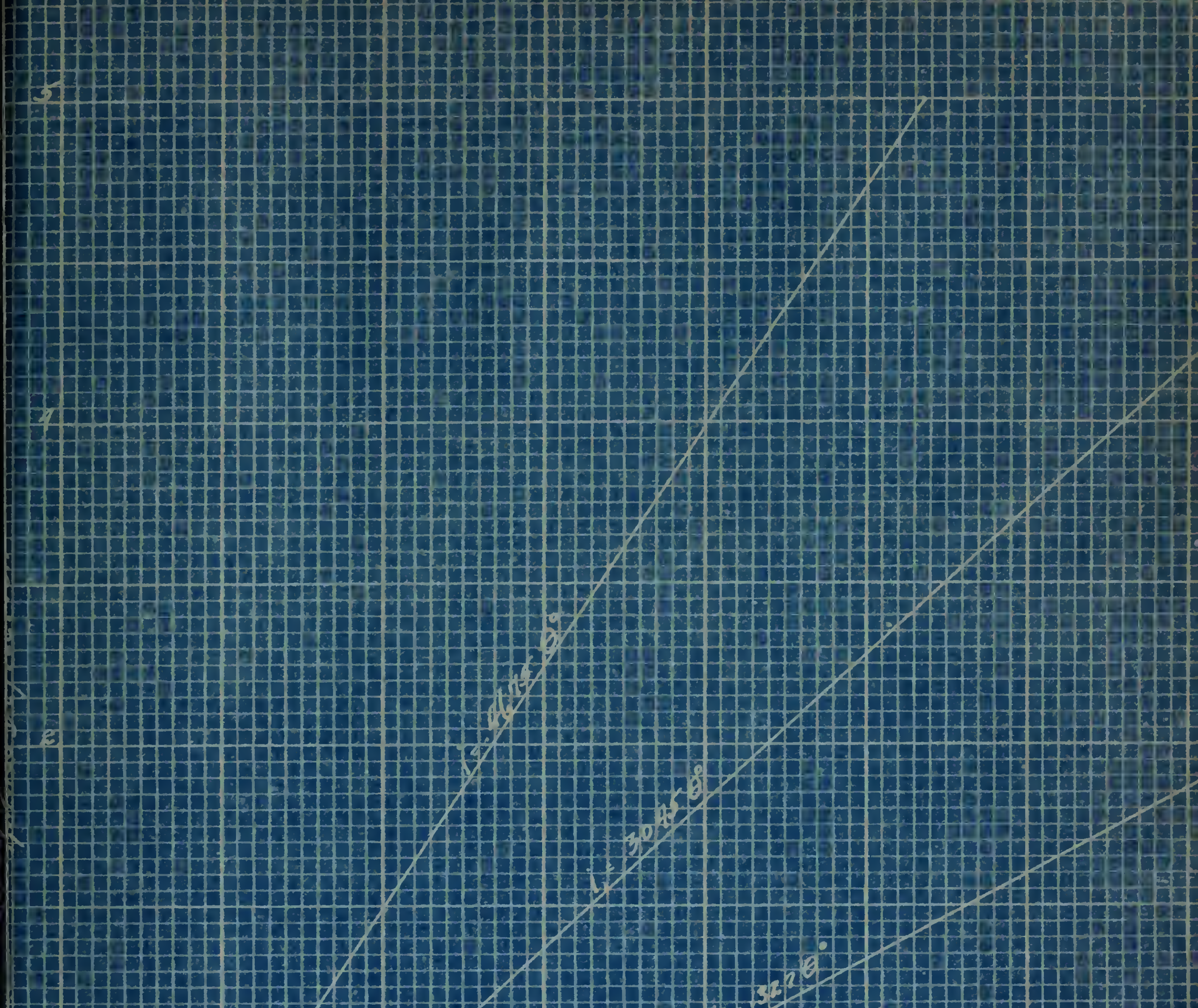

Load-Deflection
Run Number 2
Fore Mast.
Load in pounds
4500
4000
3500
3000
2500
2000
1500
1000
500
5/16
10/16
15/16
Deflection—inches

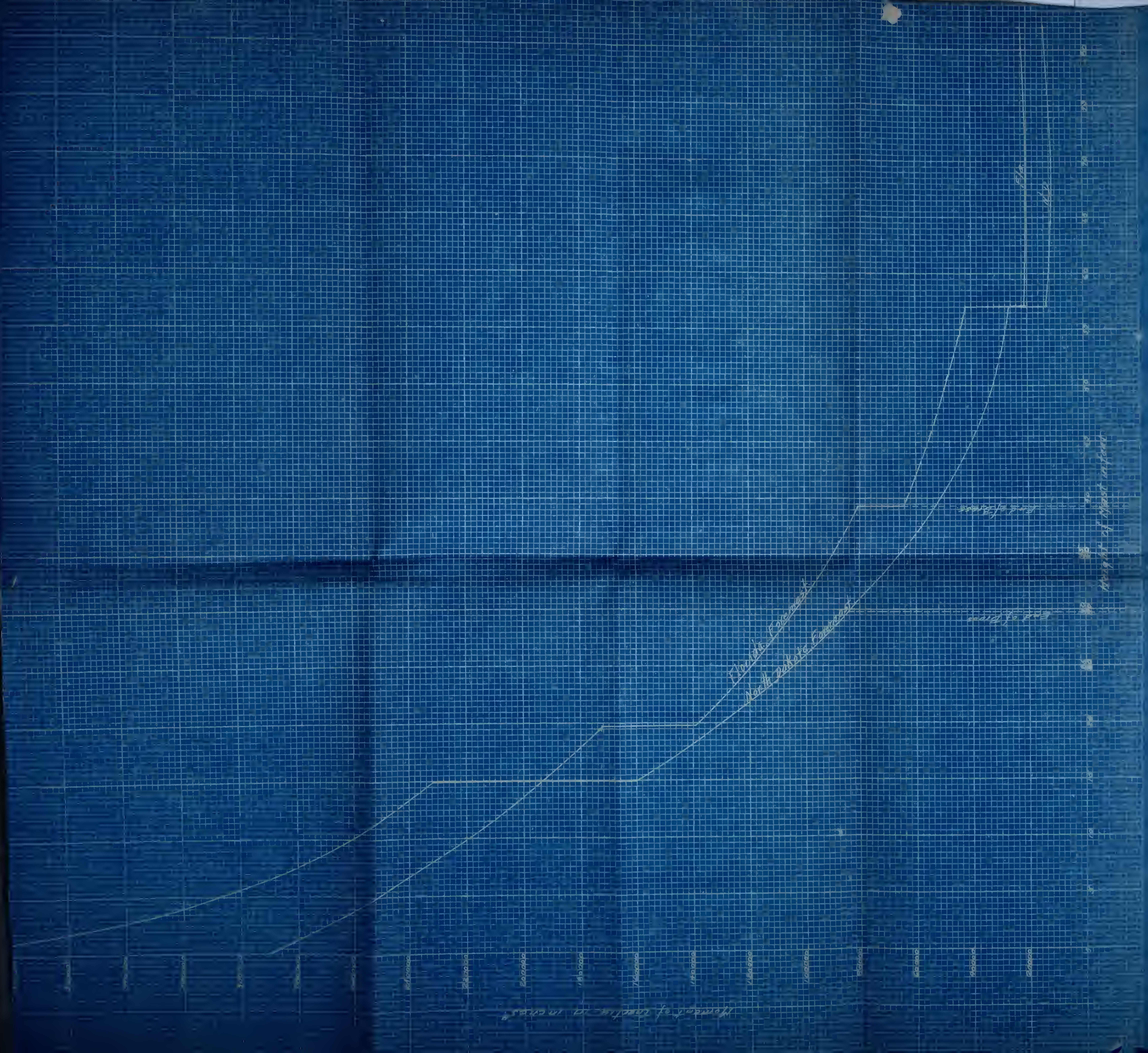

Load-Deflection.
Run Number 2
Main Road
Load in pounds
4500
4000
3500
3000
2500
2000
1500
1000
500
5/16
10/16
15/16
Deflection - inchs.


Curvature of Main Mast
Run Number 1
Maximum Load 4367 lbs.
Maximum Deflection 1 3/16"
Height of Mast in feet
90
80
70
60
50
40
30
20
10
0
8/16
16/16
Deflection in inches



Curvature of Main Mast
Run Number 2
Maximum Load 3961 lbs.
Maximum Deflection 1/16" and 1-30".


5
4
3
2
1
0
2
4
6
8
10
12
14
l = .4145 θ°
l₁ = .3045 θ
l₂ = .327 θ°
l₃ = .0305 θ°
Roll in Degrees from Vertical


Moment of Inertia in inches⁴
Height of Mast in inches

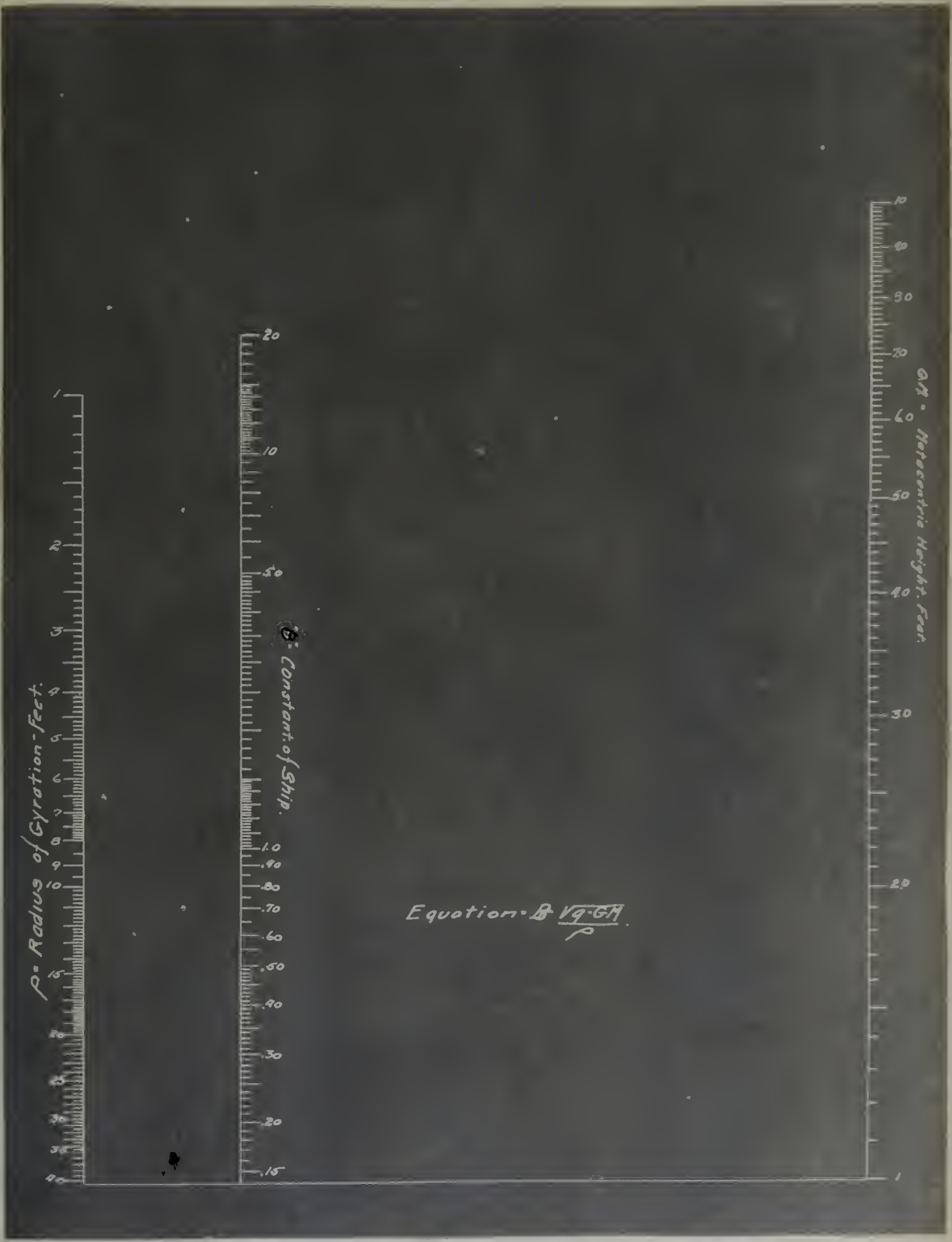
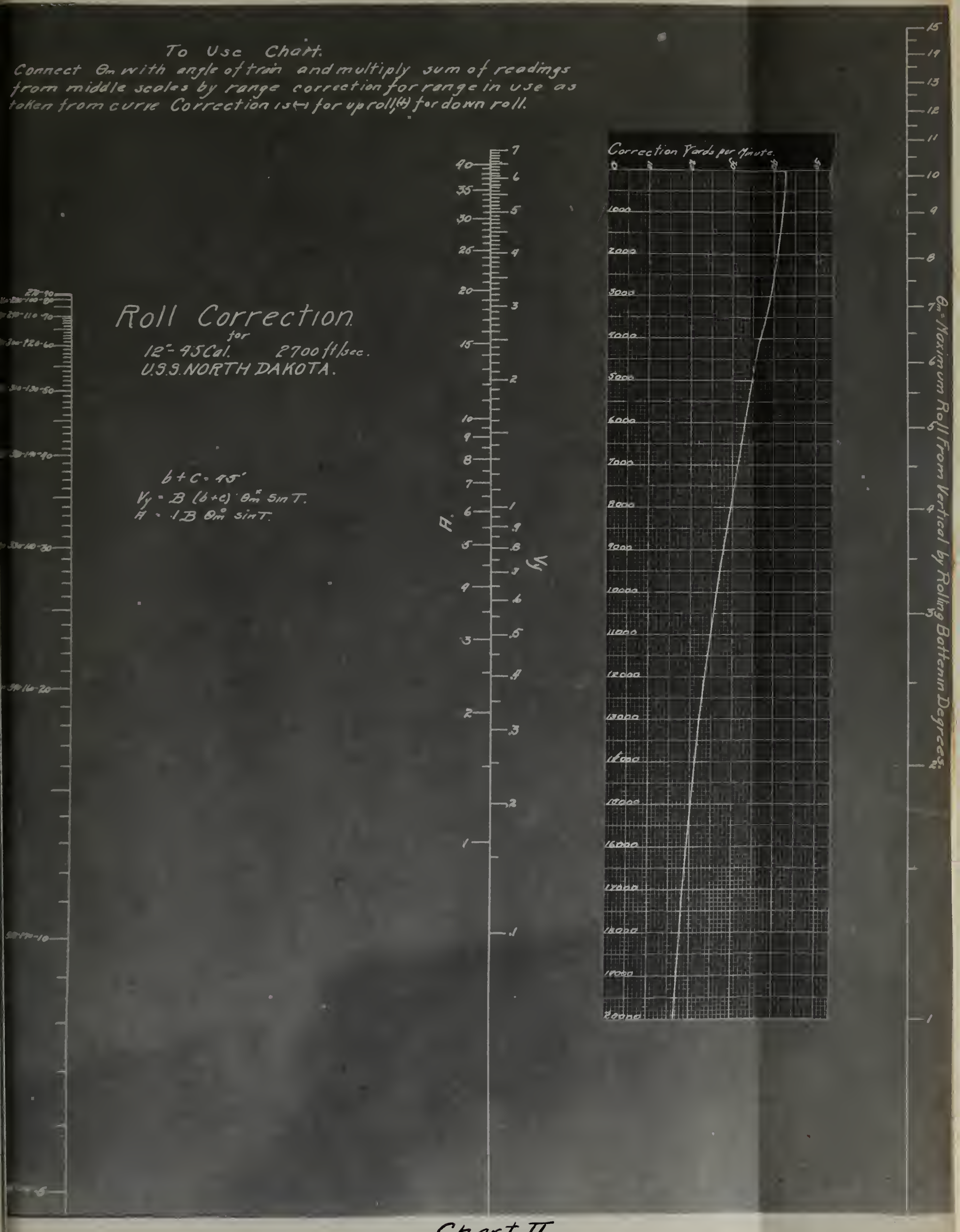

ρ - Radius of Gyration - Feet.
1
2
3
4
5
6
7
8
9
10
15
20
25
30
35
40
B - Constant of Ship.
20
10
5.0
1.0
.90
.80
.70
.60
.50
.40
.30
.20
.15
GM - Metacentric Height. Feet.
10
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1
Equation - $B = \frac{\sqrt{g \cdot GM}}{\rho}$.

Chart I.



To Use Chart.

Connect θm with angle of train and multiply sum of readings from middle scales by range correction for range in use as taken from curve Correction is (-) for up roll, (+) for down roll.

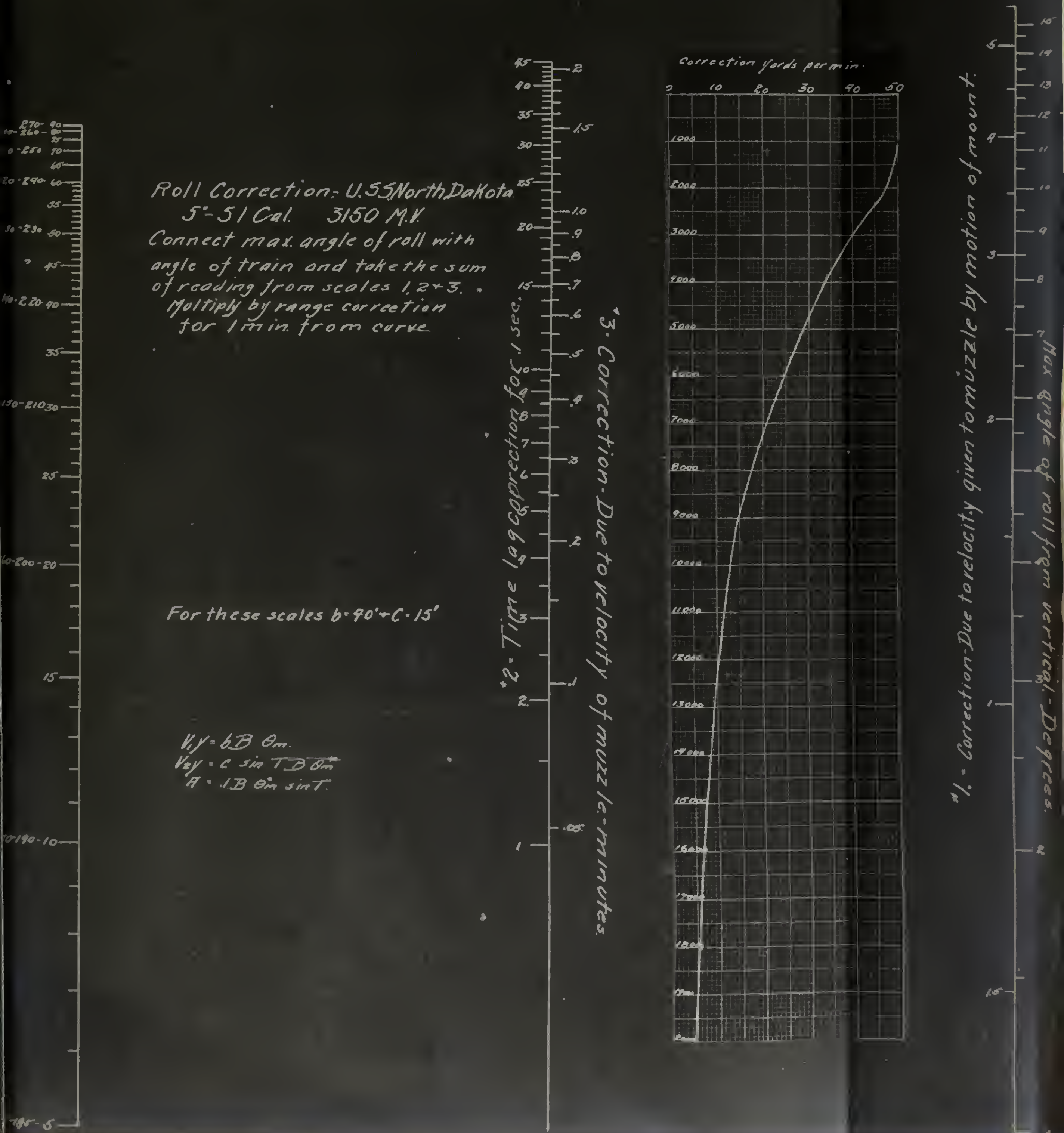
Roll Correction
for
12"-45 Cal. 2700 ft/sec.
U.S.S. NORTH DAKOTA.

$b + c = 45'$

$V_y = B\,(b+c)\,\theta_m^{\circ} \sin T.$

$A = .1 B\,\theta_m^{\circ} \sin T.$

Chart II.



Roll Correction:- U.S.S. North Dakota.
5"-51 Cal. 3150 M.V.
Connect max. angle of roll with angle of train and take the sum of reading from scales 1, 2 + 3. Multiply by range correction for 1 min. from curve.

For these scales b = 90' + C = 15'

$V_1y = bB\theta_m.$
$V_2y = c \sin T B \theta_m$
$A = .1 B \theta_m \sin T.$

Chart III.

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